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# Position location using wireless communications on highways of the future

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**Index Terms:**
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## Abstract

With recent advances in wireless communications and low-power electronics, accurate position location may now be accomplished by a number of techniques which involve commercial wireless services. Emerging position location systems, when used in conjunction with mobile communications services, will lead to enhanced public safety and revolutionary products and services. The fundamental technical challenges and business motivations behind wireless position location systems are described in this article, and promising techniques for solving the practical position location problem are treated.

# Position Location Using Wireless Communications on Highways of the Future

*T. S. Rappaport, J. H. Reed, and B. D. Woerner, Virginia Polytechnic Institute and State University*

Safety is the primary motivation for vehicle position location. In the United States, the Federal Communications Commission (FCC) has required landline telephone companies to provide 911 emergency service for many years, and in 1994 began investigating similar services for U.S. cellular and personal communication service providers [1]. Basic 911 service automatically forwards any 911 telephone calls to a public safety agency. Enhanced 911 (E-911) service improves emergency responsiveness by including the caller's automatic number identification (ANI) and street address information so that the nearest public safety agency may respond and return calls to the emergency caller. Today, the 911 operator receives very little, if any, of this information from a wireless caller. In fact, [1] indicates that at least one of every five 911 calls is originated by a cellular telephone user, and 25 percent of these users do not know their location when placing the call. In June 1996, the FCC adopted a new rulemaking order based on [1], which requires wireless service providers to support a mobile telephone callback feature and cell-site location mechanism by mid-1997, with completion required by early 1998. For *wireless* E-911 services, private branch exchanges (PBXs) which connect wireless users to the public switched telephone network (PSTN) will be required to indicate the wireless caller's telephone number, the base station location, and an estimate of the location of the caller. With these new requirements, public safety answering points (PSAPs) will have enhanced position location information on each wireless emergency call, and will have the option of requiring even more detailed position information within five years [2].

While safety is the main motivation for wireless position location, other promising applications include accident reporting, navigational services, automated billing, fraud detection, roadside assistance, and cargo tracking. Position location systems will provide new services and revenue sources for wireless carriers, greater crime-fighting capabilities for law enforcement personnel, and new methods for tracking people and parcels. Position location services will not only provide new consumer options and products for wireless carriers, but also features that could differentiate services and markets (i.e., differentiation between PCS, cellular, specialized mobile radio, and paging). Location systems will also provide wireless carriers and vendors who use position location the ability to charge for services based on location, within a particular city, cell site, or specific location such as an office, home, or car. This will allow wireless service providers to control customer usage by offering cost incentives that match service plans to the wireless infrastructure and networking resources.

In 1991, the U.S. Transportation Research Board and the National Research Council defined research needs and implementation requirements for Intelligent Transportation System (ITS) communication standards [3]. In 1993, the U.S. Transportation Research Board focused on seven unique aspects of ITS communications, including vehicle monitoring, highway automation, and traffic management systems. Specific problems targeted for research included candidate technologies for on-board vehicle location and position location from wireless base stations [4]. Meanwhile, commercial forces in the United States have created nearly 100 percent coverage of analog mobile phone system (AMPS) and paging services, as well as worldwide coverage of the global positioning system (GPS).

In the remainder of this article, we provide an overview of existing position location systems, followed by a survey of fundamental concepts in position location, a summary of advanced algorithms for position location, and a discussion of research and future issues for ITS position location for wireless systems.

## Overview of Existing Position Location Systems

A number of position location systems have evolved over the years that are useful for ITS applications. More recently these systems have become synergistic with wireless communications. Already, large shipping and trucking companies such as Highway Master and United Parcel Service have location capabilities which use existing cellular systems and GPS. Qualcomm's OmniTRACS® system provides satellite-based fleet management, whereas Highway Master uses the terrestrial cellular system. Below we provide an overview of some of the popular commercial position location systems and the communication technologies with which these systems work.

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### Global Positioning System (GPS)

GPS is the most popular radio navigation aide and has overtaken virtually all other forms of radio navigation because of its high accuracy, worldwide availability, and low cost. For ITS applications, a GPS receiver is often coupled with a wireless communications device to relay location information to the PSTN or PSAP.

*GPS is the most popular radio navigation aide and has overtaken virtually all other forms of radio navigation because of its high accuracy, world wide availability, and low cost.*

The principle behind GPS is simple, although the implementation of this time-of-arrival (TOA) system is quite complex [5–7]. GPS uses precise timing within a group of satellites and transmits a spread spectrum signal to earth on L-band (centered at 1575.42 MHz). An accurate clock at the receiver measures the time delay between the signals leaving the satellites and arriving at the receiver. This allows calculation of the exact distance from the observer to each satellite. If three satellites are visible to the receiver, triangulation can be used to find the observer's location. In practice, a lower-accuracy clock is used by the observer, and signals from a fourth satellite are used to correct receiver clock errors. The time traveled by each signal describes a sphere about the satellite. A receiver's position lies at the intersection of three spheres, providing coordinates in latitude, longitude, and altitude.

Currently GPS receivers can be found in quantity for under $200/unit with accuracy of approximately 100 m. More sophisticated units, including those used by the military or using differential GSP, provide accuracy within a few meters. Prices of GPS units are dropping rapidly as production levels and demand increase.

Reducing the cost of GPS receivers is the key to the successful deployment of GPS for ITS applications. NAVSYS Corp. has developed a low-cost GPS sensor called TIDGET™ that takes a 10 ms "snapshot" of the raw GPS sampled data and transmits this information via cellular radio to a remote site where the information and the GPS receiver location are determined [8]. A map database may be incorporated into the processing scheme to allow the position of the GPS receiver to be determined with as few as three satellites in view. The TIDGET receiver can be purchased in large quantities for about $50/unit since only a partial GPS receiver is needed. GPS/TIDGET accuracy is being tested as part of the Colorado Mayday Project with positive early results [9].

### Loran C

Loran C, developed in the 1950s by the U.S. Department of Defense, operates in the low frequency (90–110 kHz) band and uses a pulsed hyperbolic system for triangulation. It has repeatable accuracy in the 19–90 m range and is accurate to about 100 m with 95 percent confidence and 97 percent availability. Like GPS, its performance depends on local calibration and topography. The system offers localized coverage to the United States and selected countries [10]. GPS has replaced Loran C in most applications.

### Signpost Navigation

Signpost Navigation employs a large number of simple radio transmitters to accurately determine position at a mobile. These transmitters are spaced along highways and typically serve as coded beacons, where the code designates the latitude and longitude of the signpost. The transmitter signal strength indicates the relative position of the receiver to the transmitter. This navigation aid works well for limited areas such as a small city. While not originally designed as such, today's AMPS analog cellular radio system may actually serve as a signpost system, since each base station transmits a beacon signal on its forward control channel [11]. As part of the forward control channel structure, an overhead message containing a station identification number (SID) and a digital color code (DCC) is sent every 0.8 s. The SID identifies the market covered by the cellular system, whereas the DCC and forward control channel number may be used by an intelligent receiver to determine location within a cell site. When receivers have a priori knowledge of the location and DCC assignment for each base station, a standard cellular system may be used as a course position locator.

### Global Navigation Satellite System

The Global Navigation Satellite System (GLONASS), an initiative by the Russian government to provide a similar system to GPS, is in its final stage of development [12]. Although the system uses principles similar to GPS, its operation differs in several aspects. The synchronization period for GLONASS takes only 1/3 as long as GPS, typically under a minute. The integration of GLONASS and GPS receivers offers a synergistic combination to substantially reduce position errors [13].

### Automatic Vehicle Monitoring

Automatic vehicle monitoring (AVM) systems provide position location capabilities for handling large numbers of vehicles. Typical applications include fleet management, vehicle security, and emergency services. AVM systems have been available in the United States for a number of years, starting in 1968 as experimental systems, continuing in 1974 under temporary FCC rules, and in 1995 under permanent rules that recognize the new technologies and new ITS services provided by AVM [14]. In 1995, the FCC changed the name of these systems to "location and monitoring services (LMS)." In the United States, the primary band for LMS is the 902–928 MHz industrial, scientific, and medical (ISM) band, although LMS is supported to a lesser extent in several bands below 512 MHz. LMS systems are licensed systems with up to 300 W peak power for the forward link; however, they share the band with low-power unlicensed devices, such as cordless phones, wireless local area networks, and utility meter-reading systems. The band is also used by federal government radiolocation systems and amateur radio operators, so the prospect of interference between LMS and other users of the spectrum is an issue in the deployment of LMS systems [15].

### Cellular Geolocation

Cellular geolocation uses principles described in the next section, and relies on the existing infrastructure of cellular base stations. Geolocation offers position estimates of mobiles as they transmit over standard cellular frequencies. This method was demonstrated by Raytheon E-Systems (Falls Church, Virginia) in the Cellular Applied to IVHS Tracking and Location (CAPITAL) project in Northern Virginia [16, 17]. Other vendors such as KSI (Annandale, Virginia) and Associated Communications Corp. (Bala Cynwyd, Pennsylvania) are also working on this approach.

Geolocation offers some advantages to GPS since it concentrates cost at each base station and allows position location to be performed without the need of GPS at the mobile. Thus, standard cellular phones, including handheld portables, may be tracked. Service providers may also use geolocation to accurately determine capacity needs for a particular region, and may adapt the network accordingly. This approach sup-

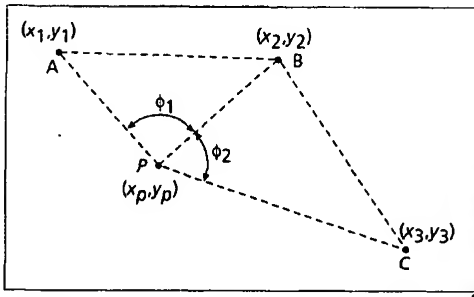
ports an E-911 implementation that is compatible with any existing mobile phone, and the position location information may be used simultaneously for vehicle traffic management, incident detection, and wireless network management.

In the CAPITAL operational test, geolocation equipment is located at selected cellular towers to collect phone usage statistics and to geolocate phones on designated roadways. In this application, it has been shown that traffic monitoring via cellular has several advantages over conventional ITS traffic monitoring techniques such as buried magnetic sensors or video cameras. These advantages include lower cost as compared to magnetic loop-based approaches, high reliability and low maintenance, and no disruption of road service for installation or repairs.

The CAPITAL system geolocates the target mobile by monitoring (at base stations) the reverse voice channel or reverse control channel transmissions from the mobile user. Multiple base stations receive the mobile signal, and the target position is determined by combining angle of arrival (AOA) estimates from each base station and time difference of arrival (TDOA) estimates between multiple base stations. AOA measurements at each base station are made using an adaptive array and a variation of the maximum likelihood techniques described in [18, 19] (discussed later). Signal time of arrival data are measured at each base station and time-stamped with a GPS time reference to determine TDOA position estimates. The impact of multipath is minimized by using highly directional adaptive antennas that offer spatial filtering [17, 20, 24]. However, it is still necessary to do additional processing to sort multipath components from direct components and to identify interfering components. Experimental results showed that position estimates were, for the most part, within 100 m of the true location, and within the accuracy proposed for E-911cellular service [16, 17]. Positions are typically fixed in less than a second, which is faster than a typical GPS configuration. The technology also works for a variety of cellular standards such as AMPS, narrowband AMPS (N-AMPS), and U.S. digital cellular (USDC). Furthermore, cellular and personal communication services (PCS) service providers are likely to use adaptive arrays in the future to increase system capacity. Thus, position location may become a natural by-product of future wireless systems.

## Position Location Fundamentals

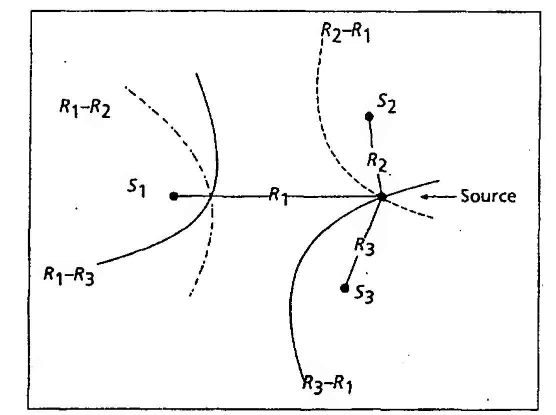
The primary function of a position location system is to locate the coordinates of a desired mobile user (called the target) with respect to a set of objects (base stations) with known positions. Position location systems may be unilateral or multilateral. In a unilateral system, a mobile unit forms an estimate of its own position based on signals received from transmitters at known locations. The GPS and the three-point problem from surveying are classic examples of unilateral systems [7, 21–23]. In a multilateral system, an estimate of the mobile location is based on a signal transmitted by the mobile and received at multiple fixed base stations. Most cellular geolocation proposals are multilateral, where the estimate of the mobile's position is formed by the network, rather than by the mobile itself.




■ **Figure 1.** *The three-point problem, also known as triangulation. Three fixed beacons (A, B, C) provide signals which allow the mobile to determine its location. The mobile must have an accurate method of measuring angles.*

Position location via wireless can be accomplished by two general methods: the AOA method and the time of arrival (TOA) method. AOA, also called direction of arrival (DOA), has been used widely in surveying, radar tracking, and vehicle navigation systems [22–24]. The location of the desired target in two dimensions can be found by the intersection of two lines of bearing (LOBs), each formed by a radial from a base station to the mobile target. A single measured angle forms a pair of LOBs and provides the target location. Instead of using the intersection of just two lines, many pairs of LOBs are used in practice, and highly directional antennas are required, making AOA difficult at the mobile. As shown in Fig. 1, AOA methods may use three base stations located at points (A, B, C), and two measured angles to deduce the location of the target at the point of intersection of two circles. This method, known as "resection" or triangulation, may be solved using trigonometry or analytic geometry, or through table lookup [22].

For radio frequency (RF) signals, AOA is usually determined at a base station by electronically steering the main lobe of an adaptive phased array antenna in the direction of the arriving mobile signal. Typically, two closely spaced antenna arrays are used to dither about the exact direction of peak incoming energy to provide a higher-resolution measurement of the AOA. The many adaptive algorithms to accomplish this steering are discussed in the folowing section. AOA is applied to the problem of direction finding (DF), where the target attempts to locate the direction of fixed sensors in order to obtain a position fix, often using high-resolution spatial analysis techniques that have been developed [24–27]. The second primary method for determining position location is with TOA measurements [28]. Since electromagnetic waves propagate at the constant speed of light ($c = 3 \times 10^8$ m/s), or approximately 1 ft/ns in a free space medium, the distance from the mobile target to the receiving base station is directly proportional to the propagation time. If the signal propagates in time $t_i$ from the target transmit-




■ **Figure 2.** *2-D hyperbolic position location solution. Two hyperbolas are formed from TDOA measurements at three fixed receivers to provide an intersection point which locates the target source. $S_1$, $S_2$, and $S_3$ represent the fixed receiver locations, and Eq. (2) is used to determine the two hyperbolas.*

ter to the ith fixed receiver, then the receiver lies at range $R_i$, where

$$R_i = ct_i. \quad (1)$$

Therefore, if a free space signal arrives at a base station receiver 10 µs after it is transmitted, the target transmitter must lie on a sphere of radius 3000 m from the base station. If TOA measurements are made at a second base station at a second location, the target position can be determined to lie on a circle since the intersection of two spheres is a circle. The three-dimensional position of a transmitter is uniquely determined by the intersection of three spheres using TOA measurements from three base stations [28, 29].

In general, direct TOA results in two problems. First, TOA requires that all transmitters and receivers in the system have precisely synchronized clocks (e.g., just 1 µs of timing error could result in a 300 m position location error). Second, the transmitting signal must be labeled with a timestamp in order for the receiver to discern the distance the signal has traveled. For this reason, TDOA measurements are a more practical means of position location for commercial systems [30].

The idea behind TDOA is to determine the relative position of the mobile transmitter by examining the difference in time at which the signal arrives at multiple base station receivers, rather than the absolute arrival time. Therefore, each TDOA measurement determines that the transmitter must lie on a hyperboloid with a constant range difference between the two receivers. The equation of this hyperboloid is given by

$$R_{i,j} = \sqrt{(X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2} - \sqrt{(X_j - x)^2 + (Y_j - y)^2 + (Z_j - z)^2}, \quad (2)$$

where the coordinates $(X_i, Y_i, Z_i)$ and $(X_j, Y_j, Z_j)$ represent the fixed receivers $i$ and $j$, and make up the unknown coordinate of the target transmitter [31]. If the source and all receivers are coplanar, a two-dimensional source location can be estimated from the intersection of two or more independently generated hyperboloids generated from three or more TDOA measurements, as shown in Fig. 2. Three-dimensional source location estimates require at least four independent TDOA measurements.

Unlike TOA measurements, the transmitted signal need not contain a timestamp, and TDOA measurements require only that the fixed location receivers have precisely synchronized clocks. This corresponds to the timing standards already provided at cellular base station sites, making TDOA more realistic than requiring each mobile unit to have an accurate clock. Atomic clocks, such as a Cesium time source, or a GPS receiver clock are typically used for timing at base stations.

It is possible to combine TDOA and AOA techniques into hybrid systems. For example, the position location system developed by Raytheon E-Systems for the CAPITAL project employs both techniques (Fig. 3) [17]. These two main classes of position location systems may be supplemented with dead-reckoning or inertial navigation techniques. Dead-reckoning can be particularly useful when buildings and terrain obscure line-of-sight propagation between a transmitter and receiver. In this case wheel rotation sensors, which measure distance traveled, or inertial navigation systems using gyroscopes are used to update the location from the last previously known position until a new position fix can be obtained.

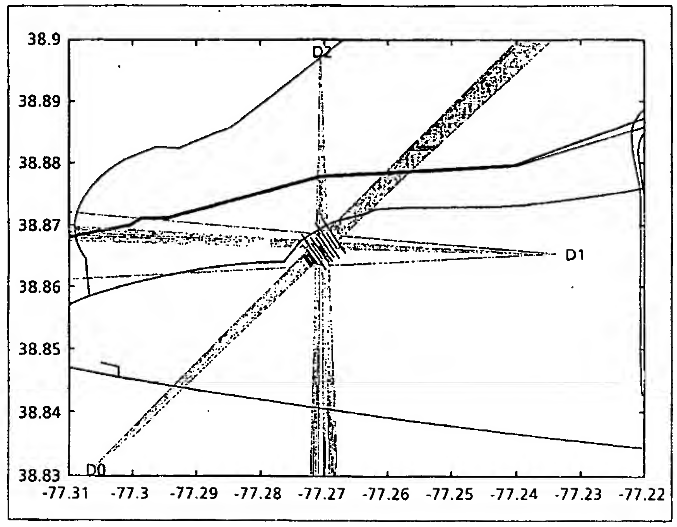


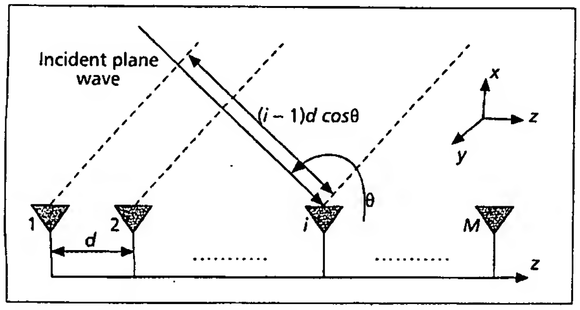

**Figure 3.** *Geolocation of a cellular signal based on TDOA hyperbolas (gold) and lines of bearing (orange) from three base station sites in Northern Virginia. This figure illustrates repeated attempts on the same signal, with the black "x" indicating the position locations. (Compliments of Joe Kennedy, Raytheon/E-Systems, Falls Church, Virginia).*

The basic position location techniques described above work well if the signals are not corrupted by noise, multipath, or interference. In practical systems, however, position errors occur due to imperfections in the channel [32]. While both AOA and TDOA techniques require a minimum of two or three base stations to determine a unique position location, new cellular or PCS systems are often designed to ensure only one high signal-to-noise ratio (SNR) link between a transmitting mobile and a base station. This is because in a conventional cellular system, base station count (infrastructure cost) and interference between adjacent cells must be minimized when first deploying the system [11]. The ability of multiple base stations to hear the target mobile is paramount to the design of position location systems. This problem is referred to as *hearability*, and it is where the design philosophy of multilateral position location systems diverges from that of wireless communications systems. Hearability is more of an issue in rural cellular systems, where coverage issues dictate the system design rather than capacity demands, which leads to more base stations and redundant coverage in cities [34].

Both AOA and TDOA techniques also rely on a direct line-of-sight path from the transmitting mobile to the base station receivers.

However, both urban and mountainous rural environments induce significant path blockage and multipath time dispersion due to reflections from and diffraction around buildings and terrain. Multipath components may appear as a signal arriving from an entirely different direction, and can lead to catastrophic errors in an AOA system [33]. Although diffraction around a building may have less severe consequences for the relative TOA of a signal in a TDOA system, multipath reflections from distant objects can lead to time distortions of several microseconds [11]. Because of their ability to resolve and reject multipath, wideband spread-spectrum systems and directional antennas will offer advantages for position location in a multipath environment [20].

Real-world channel impairments require special processing techniques to improve the resistance of both AOA and TDOA methods to noise, multipath, and interference. It is often advantageous to use more than the minimum number of TDOA or AOA receivers for a unique solution, in order to




■ **Figure 4.** *Illustration of a plane wave incident on a linear equispaced array. The dotted lines represent the phase fronts of the incident wave.*

average out errors induced by the radio channel. While this affords improved performance by combining additional information, it is usually impossible to obtain a single consistent solution in this *overdetermined* case. As a result, processing algorithms must be capable of combining many noisy and inconsistent measurements. These algorithms are discussed in greater detail in the next section.

## Advanced Algorithms for Position Location

### AOA Algorithms for Position Location

This section presents an overview of some of the more popular methods for estimating the AOA of a signal impinging on an array of antenna elements. Because a vast body of literature exists on these direction finding (DF) methods, the discussion here is kept brief, with emphasis placed on those methods most applicable to the cellular/PCS radio environment. More details on the algorithms discussed here may be found in the cited references. In particular, the overviews given in [24, 61] are excellent sources of background information on the problem of AOA estimation.

In general, an angle of arrival estimate is made from a base station using a directional antenna such as a phased array of two or more antenna elements to measure the AOA of the incident signals (Fig. 4). In general, the sensor (e.g., antenna element) spacing used in an AOA measurement is on the order of half the wavelength of the signal carrier frequency. The relatively close spacing of the antenna elements allows the time delay seen by a signal as it propagates across the array to be modeled as a phase shift. This is referred to as the "narrowband model," and is assumed to be appropriate in the development of most AOA estimation algorithms.

The accuracy of the narrowband model is dependent on the signal bandwidth, the antenna element spacing, and the quality of the receiver hardware. The narrowband model is only accurate if the signals received at each antenna element are processed (filtered, downconverted, sampled, etc.) in an identical manner. This means that each channel of the receiver (RF front-end for each antenna element) must have nearly the same frequency response, be highly linear, and use the same oscillators for all mixing and sampling operations. This type of receiver is generally known as a *coherent receiver*. The receiver is a major contributor to the cost of an AOA estimation system, where the cost increases as the number of antenna elements (and hence number of receiver channels) increases. Therefore, it is highly desirable to keep the number of antenna elements in the array to a minimum. The number of antenna elements needed in the array is strongly dependent on the signal environment and the specific AOA estimation algorithms employed. A critical assumption made for most DF techniques is that the number of incident signals is strictly less than the number of antenna elements. As discussed later, this requirement can be relaxed if properties of the incident signal are exploited; if, for example, it contains a known training sequence, or the sequence can be estimated. It should be noted that implementation of adaptive beamforming requires the same type of coherent receiver. Therefore, if smart antennas (i.e., adaptive phased arrays) are deployed at the base station, AOA estimation can be incorporated with modest additional signal processing, and such antenna systems show great promise for emerging high-capacity wireless systems [20]. The array must be carefully calibrated over all measured angles, as well as frequency and temperature. This is an expensive operation, in terms of the cost of both computational storage and periodically performing the array calibration.

The most straightforward AOA estimation approach is phase interferometry. A *phase interferometer* directly measures the phase difference between the signals received on multiple pairs of antenna elements and converts this to an AOA estimate. This approach works quite well for high SNR but will fail for strong co-channel interference and/or multipath.

Another conceptually simple approach is *beamforming*. This method can be viewed as measuring the output power of a beamformer while steering the main-beam of the array over the angular field of interest. This yields a true spatial spectrum, that is, an estimate of power distribution versus AOA. A diagram illustrating the concept of beamforming is shown in Fig. 5. The beamformer weights $w_n$ control the spatial response of the beamformer. Capon's method is closely related but has better angular resolution [35]. However, neither of these methods work well in *coherent multipath*.

Methods that work well in multipath can be derived using the maximum likelihood (ML) framework [19, 24, 36]. Different ML algorithms are obtained by making different assumptions about the incident signals. This leads to the so-called deterministic and stochastic ML methods. In multipath environments the ML methods will estimate the AOA of each path. However, implementation of these methods requires a complex multidimensional search. The dimensionality of the search is equal to the total number of paths taken by all of the received signals. This search is further complicated by the fact that the total number of paths is not known a priori and must be estimated.

Another class of methods that will work well in multipath can be derived by combining spatial smoothing with subspace-based algorithms. Examples of subspace methods include MUSIC [25] and ESPRIT [27, 37]. Normally these methods fail in multipath, but using a spatially smoothed covariance matrix in place of the conventional one allows them to operate properly [38]. Spatial smoothing methods have been combined with property-exploiting adaptive beamforming methods which estimate the spatial signature directly [38]. Estimating AOA from spatial signature vectors has several advantages over estimating AOA directly from the observed data. The principal advantage is that the search is reduced from one where the AOA of all paths must be estimated to one where only the paths contributing to the estimated spatial signature of the desired signal must be estimated. Another advantage is that more multipath components can be processed by a fixed array [33].

A class of ML methods with very useful properties can be derived by assuming that the incident signals are known rather than unknown stochastic processes [39–41]. This allows exploitation of, for example, the training sequences that exist in most digital cellular standards. An interesting application of these methods to the problem of estimating the AOA of code-

division multiple access (CDMA) signals was recently proposed in [42]. All of the AOA estimation algorithms proposed so far assume that the number of antennas in the array exceeds the number of co-channel signals. This is clearly not practical for CDMA where the number of co-channel signals is very large; therefore, none of the AOA estimation methods discussed above are applicable to CDMA. However, by assuming that the CDMA signal may be demodulated with low bit error rate (BER), an estimated waveform may be substituted for the known waveform. One implementation of this approach uses the despread soft decisions from each antenna together with the hard decisions made by the existing CDMA demodulation process. Results presented in [42] show that accurate AOA estimates of CDMA waveforms can be obtained even in highly overloaded environments.

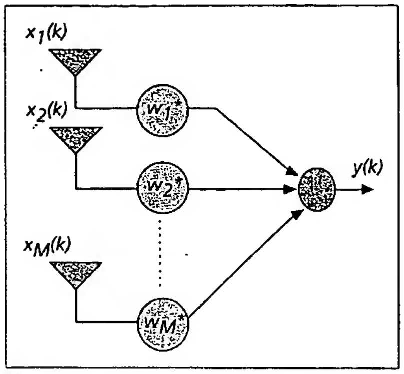


**Figure 5.** *Illustration of the beamforming structure for a phased array antenna.*

## TDOA Algorithms for Position Location

Obtaining position location estimates from TDOA measurements is a two-stage process. First, accurate estimates for TDOA values must be computed from noisy signals. Then the noisy and possibly inconsistent TDOA estimates must be processed to determine a position location estimate. The development of accurate and efficient algorithms for both stages of processing have been the subject of considerable recent research.

***Computing TDOA Estimates*** — Before evaluating the hyperbolic range equations, Eq. (2), it is necessary to estimate the range differences $R_{i,j}$, or equivalently the TDOA $t_i - t_j$. The most widely accepted method for obtaining these estimates is the generalized cross-correlation method. Suppose the transmitted signal is $s(t)$, and the signal $x_i(t) = s(t - d_i) + n_i(t)$ which arrives at receiver $i$ is delayed by $d_i$ s and corrupted by the noise process $n_i(t)$. Similarly, the signal $x_j(t) = s(t - d_j) + n_j(t)$ which arrives at receiver $j$ is delayed by $d_j$ and corrupted by the noise process $n_j(t)$. The cross-correlation function between the two signals is given by integrating the lag product of two received signals for a sufficiently long time period $T$,

$$\hat{R}_{x_i,x_j}(\tau) = \frac{1}{T}\int_0^T x_i(t)x_j(t-\tau)dt. \qquad (3)$$

The cross-correlation approach requires that receiving base stations share a precise time reference and reference signals, but does not impose any requirement on the signal transmitted by the mobile. Also note that the SNR of the TDOA estimates can be improved by increasing the integration interval $T$. Once the cross-correlation function is computed, the value of $\tau$ which maximizes Eq. (3) is the maximum likelihood estimate of the TDOA. Equivalently, an estimated cross-spectral density function can be computed in the frequency domain, and then the estimated cross-correlation function is obtained via an inverse Fourier transform.

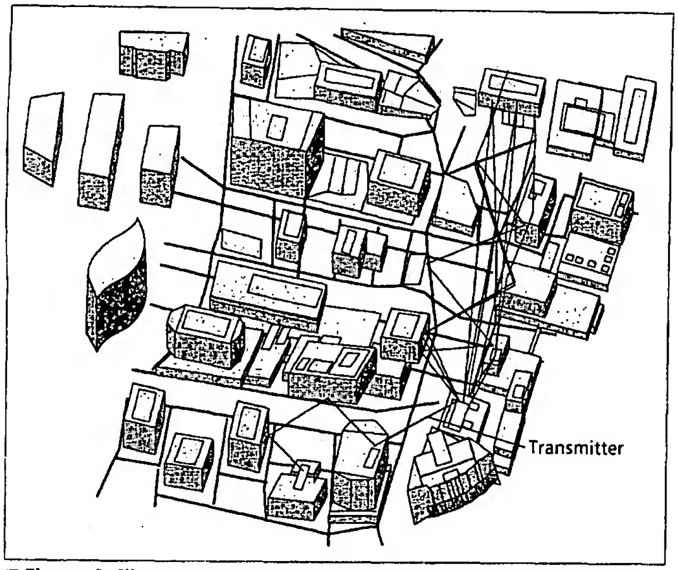
Frequency domain processing is often used because it lends itself well to filtering of the signals prior to computation of the cross-correlation function. This filtering operation is particularly important in discriminating the desired signal from arriving multipath components. While filtering techniques such as the Roth impulse response processor [35], smooth coherence transform (SCOT) [43], Eckhart filter [44], and Hähnan-Thomson (HT) are effective in reducing the effects of noise and interference on the TDOA estimates, they still experience problems in multipath [45]. This is because overlapping cross-correlation peaks due to multipath often cannot be resolved. Even if distinct peaks can be resolved, a method must be devised for selecting the correct peak value, such as choosing the largest or first peak. More recently, there has been significant research applying the theory of cyclostationary signals to improve the resolution of the generalized cross-correlation method [46, 47], which may offer improved performance in multipath environments.

***Solution of Hyperbolic Position Location Equations*** — Once accurate TDOA estimates are available, the position of the mobile transmitter may be determined by substituting the corresponding range difference estimates $R_{i,j}$ into the hyperbolic equations, Eq. (2), and solving for the Cartesian coordinates of the mobile. However, since these equations are nonlinear, their solution is nontrivial, particularly when the range estimates may be noisy or inconsistent. Much of the research in this area was originally motivated by work in the field of sonar, so there exist a number of good solutions when the receivers are constrained to lie on a regularly placed linear formation [45, 48–50]. However, the solution of hyperbolic TDOA equations is more difficult when the fixed location receivers are arranged in arbitrary fashion, which is more typical of the cellular and PCS environments.

The easiest method of solution is to linearize the equations through use of a Taylor-series expansion in which only the first two terms are retained [51, 52]. However, in some situations this method can result in significant position location errors due to geometric dilution of precision (GDOP) effects. GDOP describes a situation in which a relatively small ranging error can result in a large position location error because the mobile unit is located on a portion of the hyperbola far away from both receivers [21, 53]. Note that TDOA accuracy will be greatest when the mobile lies directly between the two receivers.

Fang [26] has presented an exact solution for the case in which the number of equations equals the number of unknown coordinates and the base stations have arbitrary locations, although this solution is unable to make use of redundant information. Other solutions have also been proposed, including spherical interpolation and a divide-and-conquer-based solution [54–57]. More recently, Chan has developed a closed form solution which is valid for an arbitrary number of TDOA measurements from arbitrarily distributed base stations [30]. The solution is valid for both close and distant sources, and approaches optimum performance for the small noise case. Chan's method performs significantly better than the spherical interpolation method, has substantially lower computational complexity than the Taylor-series method, and is able to tolerate a higher noise threshold than the divide and conquer approach.

***Measures of Position Location Accuracy*** — A number of measures have been developed to assess the performance of a TDOA position location system. Mean-squared positioning error is one obvious and widely used method which is also used for other position location techniques. Other methods




■ **Figure 6.** *Illustration of 3-D ray tracing: multipath in the urban environment of Rosslyn, Virginia [20].*

which are more specifically suited to measuring the accuracy of TDOA techniques include GDOP and the Cramer-Rao lower bound [31, 35, 52].

As noted previously, GDOP occurs when a mobile unit far away from a base station has a severely degraded position estimate, even if the TDOA range estimates are fairly accurate. This phenomenon may be used as a means of characterizing the performance of a TDOA position location system for various operating conditions and geometry. The numerical value of the GDOP is defined as the ratio of the root mean square position error to the root mean square error in the TDOA range [7, 21, 52, 58]. For a 2-D hyperbolic position location system, the GDOP is given by:

$$GDOP = \sqrt{\sigma_x^2 + \sigma_y^2} \,/ \sigma_R, \tag{4}$$

where $\sigma_x^2$ and $\sigma_y^2$ are the mean square position location errors in the $x$ and $y$ directions, respectively, and $\sigma_R^2$ is the mean-square TDOA ranging error. Clearly, the system designer would like to minimize the GDOP for a given set of conditions. The performance of a TDOA position location system is limited both by the accuracy of TDOA estimates which are available and by the accuracy with which the nonlinear hyperbolic ranging equation may be solved. The Cramer-Rao bound, which defines what is meant by "optimum performance" for an algorithm which solves Eq. (2), provides a means of assessing how close any particular position location technique comes to approaching the theoretical minimum mean squared error [30, 36, 59]. Chan's method [30] and the Taylor-Series method are the most robust, while the spherical interpolation method and Chan's method have the lowest computational complexity [30].

## THE FUTURE OF ITS POSITION LOCATION USING WIRELESS SYSTEMS

Widespread position location is in its infancy. GPS, signpost techniques, and geolocation approaches offer tremendous opportunities for improved highway safety and exciting new commercial applications. The marriage of two key technologies, position location and wireless personal communications, will completely change the way we work and travel as personal position location capabilities become ubiquitous.

In today's marketplace, the most popular cellular telephone configuration is a handheld unit that also plugs into a vehicle kit — consumers want wireless communications wherever they go, and use their phones both in vehicles as car phones and outside vehicles as handheld portables. Integrating a GPS unit with the car kit will be easy, but it remains to be seen if GPS can be integrated effectively into a portable handheld wireless phone.

Finding inexpensive ways to supplement GPS coverage when mobiles are in the shadows of urban canyons will become important for many applications. Possible remedies include ground-based GPS or other geolocation supplements; integration of the Russian GPS counterpart, GLONASS, to overcome GPS limitations; and advanced on-board navigation techniques that supplement GPS information. Indeed, in good conditions GPS is often more accurate than the maps used by emergency personnel and commercial wireless providers, which indicates more work in mapping is needed as well.

Using the existing cellular infrastructure as a signpost system is a promising inexpensive course location solution. By using some a priori knowledge of the cellular system layout, a mobile may determine its location to within a cell when certain forward control channel information is received and integrated with an onboard map or database. Cellular offers brief two-way messaging via the reverse control channel.

Cellular geolocation is another emerging position location technology and may offer some advantages over GPS, although the technology is clearly not as refined as GPS. Some advantages include compatibility with existing phones for E-911, as well as the provision of ancillary information for use in vehicular traffic monitoring, vehicular incident detection, and system planning for optimum wireless resource allocation. Placing the responsibility of position location at the base station alleviates the difficulties of integrating GPS in the handheld subscriber unit.

The major issues for cellular geolocation are ensuring that multiple base stations are capable of hearing the signal (the "hearability" problem) and contending with the errors introduced by multipath. Figure 5 illustrates typical radio propagation paths in a suburban environment which were obtained by ray tracing propagation modeling at the Mobile and Portable Radio Research Group (MPRG) at Virginia Tech.

Site-specific software planning tools and propagation measurement tools provide both spatial and temporal modeling capabilities, and are needed for design, implementation, and research of wireless systems employing smart antennas and position location. For instance, planning and building a geolocation system would require that three or more base stations be capable of receiving a signal anywhere in the service region, with well understood multipath conditions throughout the region. Software planning and simulation tools will need to incorporate ray tracing techniques to understand the spatial-temporal impact of multipath on position location accuracy.

Hardware measurement tools such as wideband channel sounders [60] that are able to determine the angle of arrival will be useful and may work in concert with spatial-temporal propagation planning tools of the future. With such a set of installation, design, and simulation tools, geolocation of a mobile could be accomplished by using inexpensive monitoring receivers and by adequate base station planning. It may

also be possible to have the base stations from different service providers at different locations to aid in the geolocation.

There will also be advantages in using fully adaptive arrays at the base station to help detect weak signals and reduce the impact of multipath and interference. The adaptive array would increase the spectral efficiency of the cellular network while simultaneously providing AOA. Certainly, new position location algorithms that are computationally efficient and more robust to multipath and co-channel interference will be needed; to develop these, researchers will require more accurate spatial-temporal multipath channel modeling tools capable of creating maps and temporal-spatial channel models, such as that shown in Fig. 6.

## CONCLUSION

This article has provided a survey of position location technologies which are being introduced for the highways of the future. Regulators and commercial services are already showing intense interest in wireless location systems, yet many challenges must be met before widespread low-cost position location becomes available. GPS, signpost, and geolocation appear to be leading candidates for wireless position location, and it is presently unclear which way the industry will go. Much work is needed to develop ubiquitous position location solutions, and it is hoped that the treatment here will help those interested in solving problems for position location systems of the future.

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# Personal locator services emerge

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**Abstract:**
Finding a mentally impaired relative, a lost child, or a criminal in a sprawling metropolitan area would be simple if the person were equipped with a personal locator device. The belief that it should be easy to find anyone, anywhere, at any time with a few pushes of a button has caught on with the advent of the Global Positioning System (GPS). People imagine a miniature device, attached to one's person, that reports ones whereabouts almost instantaneously. Add the highly practical need to find missing persons promptly, and the personal locator system (PLS) industry is born. Systems of this nature, whether based on the GPS or some other technology, are being tested throughout the world. The architecture of a PLS is outlined. Six technologies for PLS are discussed: signal direction, signal times of arrival, GPS, server-assisted GPS, enhanced signal strength, and location fingerprinting. The importance to society of this technology is also discussed

**Index Terms:**
Global Positioning System radio applications radio direction-finding

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**FINDING A MENTALLY IMPAIRED RELATIVE, A LOST CHILD, OR A CRIMINAL IN A SPRAWLING METROPOLITAN AREA WOULD BE SIMPLE IF THE PERSON WERE EQUIPPED WITH A PERSONAL LOCATOR DEVICE**

# Personal locator services emerge

HIROAKI KOSHIMA
Locus Corp.
&
JOSEPH HOSHEN
Contributing Editor

AT 11:00 ONE MORNING IN 1998, AN ELDERLY WOMAN IN OSAKA, Japan, became alarmed. Her 73-year-old husband, who suffers from dementia, had left three hours earlier and not yet returned. She did not panic, but contacted the provider of her personal locator service, Life Service Center. Within a minute, the provider found him on the first floor of a department store, simply by paging a miniature locator device secured to the man's clothes. Thirty minutes later, when the man's son arrived at the department store, his father had already left. Fortunately, the service provider continued tracking the elderly man and was able to direct the son to the third floor of an Osaka hotel. At 12:10 p.m., the two were reunited. Locus Corp. provided the system that made this possible.

The belief that it should be easy to find anyone, anywhere, at any time with a few pushes of a button has caught on with the advent of the global positioning system (GPS). People imagine a miniature device, attached to one's person, that reports one's whereabouts almost instantaneously. Add the highly practical need to find missing persons promptly, and the personal locator system (PLS) industry is born.

Systems of this nature, whether based on the GPS or some other technology, are being tested throughout the world. Some, in fact, are already deployed in Japan. The service alone can be sold by cellular companies, which base it on their wireless infrastructure. But several companies looking into the technology options plan to offer a broad array of services to the public and to businesses.

In Japan, location services are now commercially available to 72 percent of the nation's population, including Tokyo, Osaka, Kyoto, Yokohama, Nagasaki, and Hiroshima. Initially designed to support the mentally handicapped, personal locator services have expanded to serve children, the elderly, tourist groups, and security patrols, as well. They may also be used to track valuables and recover stolen vehicles. Not surprisingly, service areas coincide with wireless infrastructure deployments, which per-

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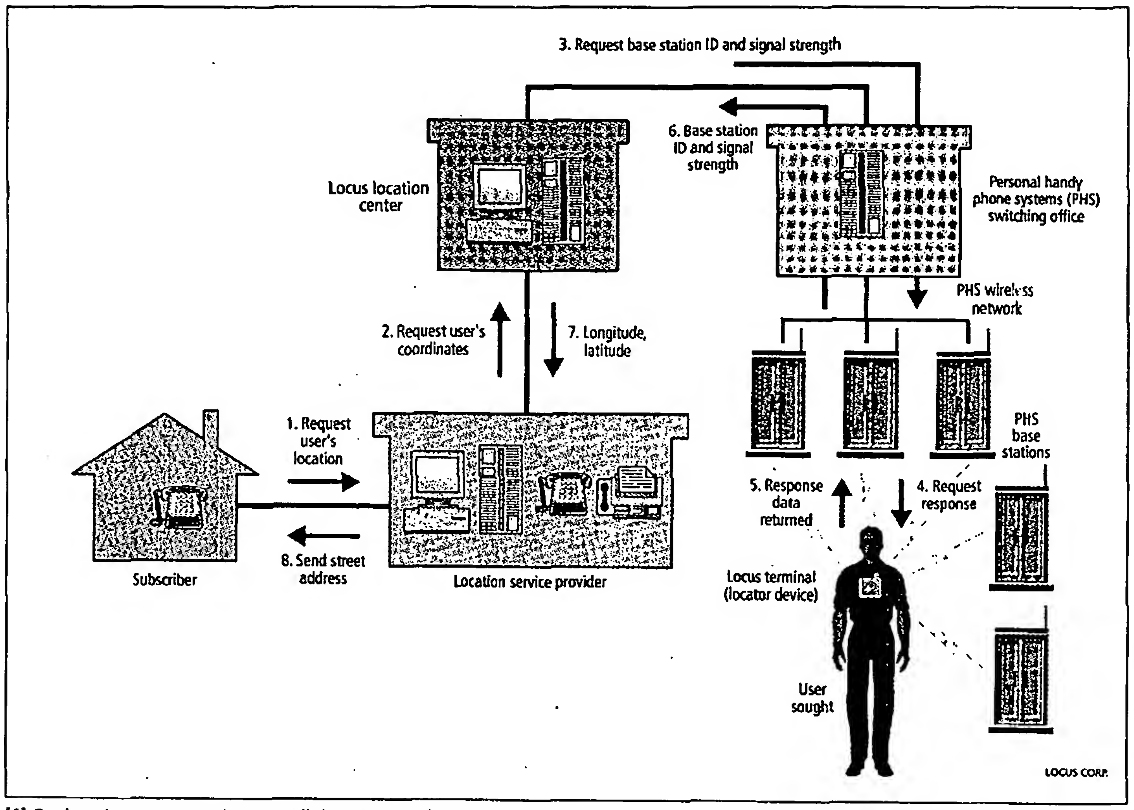



**[1] Geolocation system architecture links the user of a locator with a subscriber to the service by way of location service providers, a location center, and a wireless network. The arrows in the diagram represent the flow of data for a subscriber [lower left] seeking a user.**

sonal locators have exploited since their beginning in 1998.

In the United States, two further factors encourage the adoption of these geolocation systems. One is the need to effectively monitor offenders on parole and probation. Tagging offenders with locator devices would tighten their supervision and enhance public safety, and could even reduce the prison population. The other is the wish to provide wireless callers with enhanced 911 (E911) emergency services. For land line telephony, the location of a phone from which a 911 call is made appears automatically on the 911 operator's computer screen. But callers using cellular phones could be anywhere and unlocatable, unless location technology were applied to the wireless telephone system.

Of course, wireless services for locating vehicles have been thwarting car theft and managing fleets of cars since the mid-1980s. But unlike vehicular locators, which are less constrained by size and power, locators borne on the person have to be the size of a pager, and their power output has to be less than 1 W, because they can only carry a small battery that cannot be continuously recharged. Most challenging of all, personal locators have to be able to operate in RF-

## Defining terms

**Base station:** a land interface to a wireless network.

**Cellular digital packet data (CDPD):** a packet switching technique that uses idle voice channels for packet data calls on analog cellular networks.

**Code-division multiple access (CDMA):** a spread-spectrum [see below] wireless communication method that allows multiple users to share the same RF band by assigning each a unique code. CDMA is supported by a variety of standards, including IS-95, W-CDMA, and the upcoming cdma2000.

**Differential GPS (DGPS):** a system that improves the accuracy of GPS receivers through the use of a stationary reference GPS receiver whose coordinates are accurately known. The reference site compares its position with the position measured and determined by its GPS receiver. The difference, or measurement error, is transmitted to mobile receivers in the vicinity for their use in calculating a correction to their measured positions.

**Geolocation:** a position on the earth, usually specified in terms of longitude and latitude.

**Global positioning system (GPS):** a constellation of 24 satellites launched by the U.S. Department of Defense that transmits information enabling a GPS receiver to determine its position.

**Packet data call:** a telephony session during which packets are individually routed between the calling parties instead of a dedicated circuit being established between the parties.

**Personal handy phone systems (PHS):** a wireless phone system characterized by cell sizes outdoors of 500 to 1500 meters. The base station antenna output is up to 0.5 W and handset output is 0.01 W.

**Pseudo-random noise (PRN):** a binary code sequence (0s and 1s) that has statistical properties similar to noise.

**Spread-spectrum system:** a system transmitting signals spread over a frequency band much broader than the minimum required.


[2] The Locus locator terminal, demonstrated by co-author Hiroaki Koshima, is inserted into a safety pouch that sticks to the inside of his clothing. The pouch is intended for the mentally impaired, who are prevented from tampering with it by a special zipper. In other applications it is not required. A panic button on the locator terminal enables a user in distress to alert the system.

shielded areas like buildings, because people spend a lot of their time indoors.

### ONE PLS ARCHITECTURE

A personal locator system is likely to involve a service provider, a location center, and a wireless network. In this setting, three scenarios, each involving a different operating mode, are possible. The person bearing a locator device either is being sought by a subscriber to the service, or is seeking help from the subscriber, or, as in the case of a parolee, is having his or her whereabouts monitored continuously.

Consider again the introductory example, but from a system architecture perspective. It is representative of the first scenario, based on the paging mode, wherein the person with the locator device is sought. In this instance [Figs. 1 and 2], the subscriber calls the service provider, giving the operator there a password and the "wanted" person's identification (user) number (ID). The operator enters the ID into a computer, which transmits it to another computer at the location center. That machine calls the locator device, in effect paging it to establish communication through the PHS wireless telephone switching office (where PHS stands for personal handy phone systems). Immediately the office forwards the call to the wireless base station nearest the locator.

Once communication is established between the center and the device, the center asks the device for the signal strength data and IDs of any base stations in its vicinity. The locator replies, and from those inputs, plus RF database information on the base stations, the center computes the locator's coordinates. [Details of the geolocation technology behind this architecture follow in "5. Enhanced signal strength," p. 46.]

These coordinates are transmitted to the service provider's computer, which displays the missing person's position on a street map for the service operator to report to the subscriber. The user's location is continuously updated on the service provider's map as long as the location center maintains its call connection to the locator device.

In a second scenario, surrounding the emergency mode, the user of the locator is lost or in dire straits of one sort or another, and so presses the device's panic button. The locator calls the location center, which computes the user's position and alerts the service provider, which in turn alerts the subscriber to the user's situation.

The system can employ either packet data or voice channel communications. If a data channel is used, the service takes about 8 seconds to obtain a geolocation fix. But if a voice channel is used, the wait could last up to 33 seconds because of processing differences between the two channel types.

Several minutes may be added by communication between the

**1. REQUIREMENTS FOR LOCATING EMERGENCY CALLS FROM MOBILE PHONES [a]**

| System accuracy required: | | System accuracy acceptable: |
|---|---|---|
| with network solution | with handset solution | if this percentage of calls achieves required accuracy |
| 100 meters | 50 meters | 67% |
| 300 meters | 150 meters | 95% |

[a] September 1999 FCC directive revising E911 geolocation accuracy.

## 2. SOME LOCATION TECHNOLOGY DEVELOPERS

| Company | Technology | Availability | Web address |
|---|---|---|---|
| Cambridge Positioning Systems Ltd. Cambridge, UK | Time difference of (signal) arrival (TDOA) | In UK 1999; internationally, this year | www.cursor-system.com |
| Cell-Loc Inc. Calgary, Alta., Canada | TDOA | Second quarter of 2000 | www.cell-loc.com |
| KSI Inc. Annandale, Va. | Angle of (signal) arrival | In prototype testing; commercial system delivery early 2001 | www.TeleSentinel.com |
| Locus Corp. Osaka, Japan | Enhanced signal strength | In Japan since 1998 | www.locus.ne.jp |
| Qualcomm Inc. San Diego, Calif. | Assisted global positioning system (GPS) | Now in testing | www.qualcomm.com |
| Lucent Technologies Murray Hill, N.J. | Assisted GPS | Now in testing | www.lucent.com |
| SiRF Technology Inc. Santa Clara, Calif. | GPS and assisted GPS | Chip sets and intellectual property available since 1996 | www.sirf.com |
| SnapTrack Inc. San Jose, Calif. | Assisted GPS | To wireless carriers and device manufacturers | www.snaptrackinc.com |
| Teletrac Inc. Garden Grove, Calif. | TDOA | To commercial vehicle fleets since 1997 | www.teletrac-online.com |
| TruePosition Inc. Wayne, Pa. | TDOA | Since 1998 | www.trueposition.com |
| US Wireless Corp. San Ramon, Calif. | Location FingerPrinting (proprietary) | Now in beta field trials; commercial network operational by end 2000 | www.uswcorp.com |

service's operator and the subscriber. Such a human interface may be necessary given the complexity of Japanese city-addressing schemes. Otherwise, subscribers using personal computers may obtain the information directly from the computer of either the service provider or location center.

Both the emergency and paging operating modes of personal locator systems are characterized as intermittent. In addition, a continuous automatic mode, in which the system polls the locator nonstop, is possible. Strictly speaking, the polling is periodic rather than continuous, but the latter term is more common.

Of the three locator modes, this last requires the most RF bandwidth and battery power. If it were implemented with a continuous voice call between the system and the locator, the expense would be beyond the reach of most applications. Assuming a minimal 5 cents per minute for airtime, such a connection would cost US $72 a day—and also drain the locator battery within a few hours.

Packet data calls between the locator and the rest of the system are far more economical. In the packet version, the locator is likely to be polled every few minutes, exchanging 100 bytes or so with the system in a fraction of a second. Given a 3-minute polling interval and a 1-cent-per-poll cost, the daily cost per locator would be only $4.80. Note, too, that for most of the time the locator would be in standby mode, conserving valuable battery charge. Another plus, upcoming third-generation mobile wireless telephony will increase the availability of packet data communications.

### SIX TECHNOLOGIES

A personal locator system could use any of several technologies. Among the most common methods are angle and time difference of the signal's arrival, global positioning system (GPS) and the more recent assisted GPS, enhanced signal strength, and location fingerprinting.

### 1. SIGNAL DIRECTION

The simplest is based on measuring the direction of a signal received from an RF transmitter at a single point. This can be done by pointing a directional antenna along the line of maximum signal strength. Alternatively, signal direction can be determined from the difference in time of arrival of the incoming signals at different elements of the antenna. A two-element antenna is typically used to cover angles of ±60 degrees. To achieve 360-degree coverage, a six-element antenna can be used.

A single mobile directional antenna can give only the bearing, not the position, of a transmitting object. (The single bearing can be combined with other information, such as terrain data, to provide location.) Such an antenna is generally used to approach and locate objects up to several kilometers away. A common use of this technique is tracking RF-tagged wildlife. The same basic technique is used by LoJack Corp., of Dedham, Mass., in its system for finding stolen vehicles.

With two directional antennas spaced well apart, however, the position of a transmitting device in a plane can be computed. In this method, also known as the angle of arrival (AOA) method, transmitter position is determined from the known (fixed) position of the receivers' antennas and the angle of arrival of the signals with respect to the antennas.

Angle measurement precision affects the accuracy of positioning calculations, as does the geometry of the transmitting device and receiving antennas. For example, if a transmitter is too near a line drawn between two receiving antennas, its measured position could be off by more than the distance between the antennas. Fortunately, multiple receiver antennas distributed throughout the area of coverage enable the cellular system to select those antennas that introduce the smallest error.

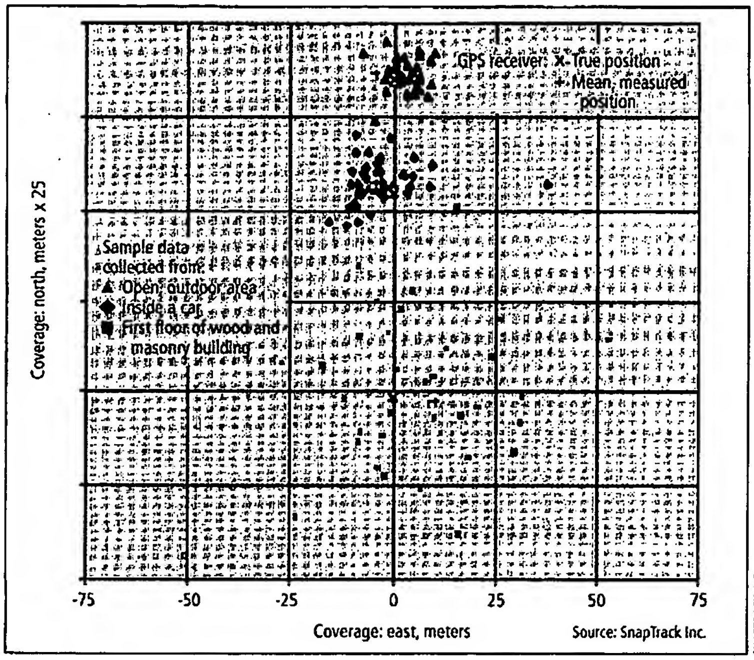
### 2. SIGNAL TIMES OF ARRIVAL

Similarly, the time difference of arrival (TDOA) between signals received at the geographically disparate antennas can be used to determine position. Given the speed of light and known transmit and receive times, the distance between the mobile locator and receiver antenna can be calculated.

Accurate clocks are of the essence here, because an error of 1 µs in time corresponds to an error of 300 meters in space. Also, all clocks used must be synchronized. But as synchronizing the mobile locator clock is usually impractical, at least three receiving antennas are required for the calculation.

Sometimes the calculations produce ambiguous results, which can be resolved by considering signals received at a fourth antenna. As with the angle of arrival method, the relative positions of receivers and transmitter affect computational errors.

In an alternative time difference scheme, the locator and the antennas reverse roles:




SNAPTRACK INC.

**[3] These are test results from the server-assisted GPS (global positioning system) technique. They show that an open outdoor area provides the most accurate location readings [at top]. Out of each group of data points, 68 percent fall within 6, 12, and 32 meters of the receivers outdoors, inside a car, and in a building, respectively.**

**The deviation of the receiver's mean measured position [+] from its true position [x] is largely due to the multipath effects of reflected signals. The increased scatter of data points inside the building or car results primarily from the reduced signal-to-noise ratio there.**

**(To avoid clutter, the data points drawn on the chart are a subset of the points collected. Note, too, that the GPS receiver antenna was not outside but inside the car, placed near the user's head.)**

the antennas are transmitters and the mobile locator a receiver. This technique is known as forward link trilateration (FLT). This is relatively simple to implement in some code-division multiple access (CDMA) wireless systems, where the time difference of arrival can be determined from the phase difference between pseudo-random noise code sequences of 0s and 1s transmitted from two antennas.

### 3. GLOBAL POSITIONING SYSTEM

The global positioning system (GPS) relies on a constellation of 24 satellites. It, too, employs signal timing to determine position, but the mobile locator is a receiver and the orbiting satellites are transmitters. The satellites transmit spread-spectrum signals on two frequency bands denoted L1 (1575.42 MHz) and L2 (1223.6 MHz). The signals are modulated by two pseudo-random noise codes, the P (precision) code and C/A (coarse/acquisition) code. The GPS signal is further modulated with a data message known as the GPS navigation message. Note that only the C/A code in the L1 band is used in civilian applications and hence is of interest here.

To acquire the satellites' signals, the GPS receiver generates a replica of the satellites' pseudo-random noise codes. The GPS navigation message can be demodulated only if the replica can be matched and synchronized with the pseudo-random noise codes received. If the receiver cannot match and synchronize its replica, the GPS signal appears to the receiver as noise. Matching the pseudo-random noise codes and using the satellites' navigation message also enables the receiver to calculate the signal transmit time as well as the coordinates of the satellites.

The accuracy of GPS position calculations depends partly on measurement accuracy and partly on satellite configuration. Measurement errors depend on physical parameters, such as ionospheric delays and orbital uncertainties, and on the selective availability (SA) factor, introduced by the U.S. Department of Defense to degrade satellite data for nonmilitary users. Total measurement errors are estimated at 35 meters; without selective availability, they are reduced to 8 meters.

The configuration of the GPS satellites at the time of the measurements adds further distortion. If those in sight are scattered throughout the sky, the measurement error is multiplied by about 1.5. If they are clustered together, the multiplier is 5 or more.

To estimate actual position accuracy, it is necessary to combine the measurement errors with the errors introduced by the spatial disposition of the satellites. To determine its position, a GPS receiver calculates its $x$, $y$, and $z$ coordinates as well as the time the satellite signals arrive. Data must be acquired from at least four (and preferably more) observable GPS satellites. When fewer than four satellites are in view, in areas like city canyons, one remedy is a hybrid approach, augmenting GPS with the land-based measurements called forward link trilateration. To illustrate, the use of two GPS satellites and two cellular base stations would suffice to determine a locator's position.

The unobstructed line of sight to the orbiting transmitters is important. The satellite signals are weak (below $10^{-15}$ W) when they arrive at a receiver's antenna, and are further weakened upon entering a building. Moreover, a conventional GPS receiver could take several minutes to acquire the satellite signals and therefore tends to operate continuously rather than be turned on and off for each acquisition. The drain on the receiver's battery is significant.

### 4. SERVER-ASSISTED GPS

To combat the shortcomings of GPS, an innovative technique known as server-assisted GPS was introduced in 1998. The idea is to place stationary servers throughout the area of coverage to assist mobile receivers to acquire the GPS signals. In effect, the servers are stationary GPS receivers that enhance the mobile GPS receiver's capabilities by helping to carry their weak signals from satellites to locator.

The server includes a radio interface, for communicating with the mobile GPS receiver, and its own stationary GPS receiver, whose antenna has full view of the sky and monitors signals continuously from all the satellites within view.

To ask a mobile GPS receiver for its position, the server feeds it satellite information through the radio interface. Included in this information is a list of observable GPS satellites and other data that enable the mobile receiver to synchronize and match its pseudo-random noise code replicas with those of the satellites. Within about a second, the GPS receiver collects sufficient information for geolocation computation and sends the data back to the server. The server can then combine this information with data from

the satellites' navigation message to determine the position of the mobile device.

With the assisted GPS approach, the mobile receivers conserve power by not continuously tracking the satellites' signals. Moreover, they have only to track the pseudo-random noise code and not extract the satellites' navigation message from the signal, in effect becoming sensitive enough to acquire GPS signals inside most buildings [Fig. 3].

In addition, the assisted version of the technology attains greater accuracy. Because the actual position of the stationary GPS receiver is known, the difference between that and its measured position can be used to calculate a correction to the mobile receiver's position. In other words, assisted GPS is inherently differential GPS (DGPS), which counters some of the inaccuracy in civilian GPS service. (The most accurate GPS service is reserved for military use.)

Just last June, Lucent Technologies Inc., of Murray Hill, N.J., announced that its wireless assisted GPS had attained an accuracy of better than 5 meters outdoors—an achievement attributable to the differential GPS capability of assisted GPS. More good news in this field was announced by SiRF Technology Inc., of Santa Clara, Calif., in the form of a postage-stamp–sized chipset (Star II) with built-in DGPS. In addition to providing improved GPS capability, it offers reduced power consumption and greater accuracy, as well as performing well at handling weak signals by using network assist.

## 5. ENHANCED SIGNAL STRENGTH

If no obstructions are present, computing the position of a mobile locator is straightforward for both the signal timing and signal strength methods. When timing is used, the speed of light multiplied by the time a signal takes to propagate between the two points gives the distance between them.

For the signal strength method, the distance between two points can be determined from the signal attenuation between the points. However, direct line contact seldom exists inside buildings, where signal attenuation is usually unknown and many indirect paths between transmitter and receiver are likely. While techniques exist for reducing this multipath effect, it cannot be eliminated, and the errors it produces are difficult to predict. Multipath effects impede signal timing methods somewhat, but affect signal strength methods still more.

In addition, signal strength is very sensitive to antenna orientation, attenuation by obstructions, and other operating conditions. In contrast, signal timing is unaffected by antenna orientation and is less sensitive to attenuation.

Nonetheless, an enhanced signal strength (ESS) method that overcomes such impediments as multipath effects, attenuation, and antenna orientation has allowed the deployment of personal locator systems in PHS service areas in Japan. Such a system takes in three-dimensional information on the lay of the land, buildings, elevated highways, railroads, and other obstructions, and uses it to simulate the RF signal propagation characteristics of every PHS wireless transmitting antenna in the area of interest. The location system center stores the results in an RF database.

The position of a mobile locator is determined by getting it to measure the signal strength of preferably three to five base stations. From this input plus information from the base stations' databases, the system can calculate the position of the locator. The mean accuracy of the ESS is 40–50 meters. Inside large public buildings, with a PHS base station on every floor, the system can indicate a specific floor level. In subway and railroad stations, the availability of base stations makes it possible to find an individual on a specific track.

The stand-alone locator used by Locus Corp.'s enhanced signal strength method [again, Fig. 2] weighs only 58 grams and can operate for 16 days on a single battery charge. The ESS geolocation capabilities are also available in a standard PHS phone handset, in which the firmware has been modified. Presently, researchers in Japan are investigating how to apply ESS technology to other wireless phone systems.

## 6. LOCATION FINGERPRINTING

Instead of exploiting signal timing or signal strength, a new technique from U.S. Wireless Corp., of San Ramon, Calif., relies on signal structure characteristics. Called location fingerprinting, it turns the multipath phenomenon to surprisingly good use: by combining the multipath pattern with other signal characteristics, it creates a signature unique to a given location.

U.S. Wireless's proprietary RadioCamera system includes a signal signature database of a location grid for a specific service area. To generate this database, a vehicle drives through the coverage area transmitting signals to a monitoring site. The system analyzes the incoming signals, compiles a unique signature for each square in the location grid, and stores it in the database. Neighboring grid points are spaced about 30 meters apart.

To determine the position of a mobile transmitter, the RadioCamera system matches the transmitter's signal signature to an entry in the database. Multipoint signal reception is not required, although it is highly desirable. The system can use data from only a single point to determine location. Moving traffic, including vehicles, animals, and/or people, and changes in foliage or weather do not affect the system's capabilities.

## WHAT'S PLS GOOD FOR?

In the United States, the need to provide wireless phone users with emergency 911 services has been one of the spurs to the development of location technologies. Today, an enhanced 911 (E911) emergency call made over a land line is routed to a public safety answering point (PSAP), which matches the caller's number to an entry in an automatic location information database. When the match is made, this database provides the PSAP with the street address plus a location in a building—maybe the floor or office of the caller handset. So quickly is the caller located that the emergency crew can respond within 5 to 7 minutes on average.

But the very mobility of wireless handsets rules out a simple database relationship between phone number and location. In fact, the response to a wireless call can be 10 times longer than for a land-line call—far from ideal in an emergency.

Accordingly, the U.S. Federal Communications Commission (FCC) in Washington, D.C., directed operators of wireless phone services to enable their E911 services to locate callers. The directive specified two phases. The first required an accuracy of several kilometers by April 1998 and the second, an accuracy of 125 meters with 0.67 probability by 1 October 2001. While the first phase needed only software changes to the system, the second requires the adoption of new location technologies.

The original FCC directive for Phase II also required support for existing handsets, which implied that only network upgrades would be acceptable. Yet a network-only solution would preclude the use of emerging technologies, such as assisted GPS, because that would require handset modification in addition to any network infrastructure and software changes. All users might not bring in their handsets for modification, severely complicating support for handsets already in service.

To ease the introduction of new technologies, in September 1999, the FCC modified its original Phase II directive to permit handset-enabled solutions and also to tighten the accuracy required [Table 1].

In addition to the many technical roadblocks to implementing the E911 directive, an even greater obstacle is cost. Upgrading all the wireless networks will cost billions of dollars. Cost recovery is the central issue for cellular service providers. Though wireless subscribers are the most likely source of recouping the cost, the government has made no formal decisions yet.

Presently, only the U.S. government requires its wireless companies to add caller geolocation to their E911 services. But as the country is a major telecommunications market, many manufacturers of wireless telecommunications equipment elsewhere

are developing approaches to meet the commission's directive.

In an international development, a working group of the European Telecommunications Standards Institute (ETSI), based in Sophia Antipolis, France, is currently drafting a standard for supporting location services for the Global System for Mobile Communications (GSM). Currently, GSM is the most common mobile wireless system in the world and available in more countries than any other wireless system.

## MONITORING TOPS SERVICES LIST

Wireless E911 just helps the individual. But monitoring the mentally impaired and criminals could have even greater impacts on society at large. With the changing demographics of the developed world, the percentage of individuals over age 65 will soar over the next several decades. So will the number of elderly afflicted with age-related mental impairments. Most of the four million or so U.S. patients diagnosed with Alzheimer's disease are over 65.

Recall how personal locator technology helped a family find a mentally impaired elderly man, fortunately within 40 minutes or so. But what if many hours passed before anyone noticed that the man was missing? What if he had run into some kind of difficulty during that time? Being mentally impaired, he would be unlikely to press the panic button. An automatic polling system could solve this problem by checking whether the man was within a defined polygonal area or not and alerting the location service and the family whenever he was not.

As the population ages, the need for and cost of long-term care are likely to increase, too. Today it costs over \$30 000 per year in the United States to care for a patient in a nursing home. Systems that monitor the whereabouts of the mentally impaired elderly could help them live longer in their communities and spend less time in institutions.

Criminal justice is another area of social concern where personal locators could intervene. The United States leads industrial nations in the percentage of its population incarcerated. In 1997, according to U.S. Department of Justice statistics, almost 1.8 million people were serving time in U.S. jails and prisons, and a further 4 million were in parole and probation programs. In comparison, in Japan in 1992, only 45 000 were serving prison terms while 90 000 were on parole or probation.

The high human and monetary cost of corrections could be cut by new technologies, such as personal locator systems, that would reduce prison populations and improve the monitoring of parolees and persons on probation. First-generation monitoring systems, introduced in the mid-1980s, track the location of the offender in a very confined area, such as the home. They enable the corrections system to verify that a parolee stays there during specified periods, 6 p.m. to 6 a.m., say. But by day, when the offender is presumably at work, these systems can do nothing.

Second-generation monitoring systems do better. A tamper-proof personal locator is fastened on the offender and tracked continuously and automatically over a wide area. [See "Keeping tabs on criminals," *IEEE Spectrum*, February 1995, pp. 26–32.] The newer system compares the actual with the supposed positions of the offender, as stored in a database. Any violation, or any tampering with the locator, and the system alerts the appropriate corrections or law enforcement agencies.

The goal is to verify that parolees and probationers comply with the directives imposed by the corrections system as to where and when they should and should not be by day and night. For example, a child molester is excluded from school areas, and a stalker is excluded from areas near the home and workplace of the victim.

Storage of the offender's ongoing whereabouts in an electronic file benefits law enforcement agencies in other ways. The record can be used to exclude or include a monitored offender as a suspect in a crime by comparing events at the crime scene with the file entries.

In 1996 two companies, Advanced Business Sciences Inc. (ABS) of Omaha, Neb. (www.abscomtrak.com), and Pro Tech Monitoring Inc., located in Palm Harbor, Fla. (www.ptm.com), were the first to introduce GPS-based continuous monitoring systems for criminal offenders. These systems are deployed in, among other places, Michigan, Minnesota, Florida, Colorado, Wisconsin, Pennsylvania, South Carolina, Arizona, Ohio, Texas, and Nebraska. More recently, BI Inc., headquartered in Boulder, Colo. (www.bi.com), the leading manufacturer of first-generation offender monitoring systems, began testing its version of a GPS-based system.

The Pro Tech Monitoring, ABS, and BI systems all include a personal locator, a wireless telephone interface, and a location center. The personal locator has two parts, a GPS unit and an ankle bracelet [Fig. 4]. The ankle bracelet, which employs tamper detection circuitry, uses a low-power transmitter with a range of about 50 meters. The GPS unit consists of a GPS receiver, a wireless phone component, and a receiver to detect the bracelet signal. The offender carries the GPS unit by hand, or in the case of the ABS system, wears it on a belt.

**[4] The geolocator in an offender-monitoring system from Advanced Business Sciences Inc. includes [clockwise from top right] a GPS unit, an ankle bracelet, and a docking station for use in recharging the GPS unit.**

**The unit, which can be worn on a belt, weighs 0.8 kg; its battery lasts for up to 48 hours between charges. The docking station includes a remote alcohol tester.**

Should the GPS unit fail to detect the bracelet signal (probably because it is out of range) or should the bracelet circuitry detect tampering, the unit will alert the location center through its wireless interface. What's more, the unit monitors its own position by means of its GPS receiver whenever the satellite signals are detectable, primarily outdoors.

The GPS unit can operate in either of two modes: autonomous or continuous. In autonomous mode, it logs the offender's location in its internal memory. It compares this position with an on-board database of exclusion and inclusion zones for the offender. When it detects a zone or other violation, it alerts the location center with a wireless call. In this mode, once or twice a day the GPS unit dials the location center and updates it with the logged data.

Operation in autonomous mode of course avoids the costly continuous voice-type wireless connections. Using the far less expensive, packet-based, cellular digital packet data (CDPD) wireless phone connection, the GPS unit can maintain contin-

uous real-time contact with the location center—the second operating mode. Unfortunately, however, CDPD is unavailable in many areas.

Splitting the locator in two—into a bracelet and GPS unit—offers a simple recharging strategy. The unit's batteries usually require a daily recharging to power the GPS unit. At night, when the offender is typically required to be at home, the unit is placed in a docking station for recharging, while maintaining contact with the location center all the while and sending information whenever appropriate.

## PRIVACY, SECURITY STILL ISSUES

Confidentiality of information about a person's whereabouts is a serious concern for location technology. Databases already store large amounts of personal information, including medical data, marketing preferences, and credit information. Lax security could lead to serious abuse of this data. Access to a database of location information could aggravate this situation by further exposing a person's movements. Moreover, it can have real-time implications. For example, someone could find and harm a victim.

The location information stored in databases needs to be secured, as does the tracking and locating process itself. As RF communications are used, eavesdropping is a possibility. To reduce this risk, location information can be encrypted or transmitted using coded signals employing such spread-spectrum technology as CDMA.

Privacy protection can also depend on the technology used. For example, in GPS or the enhanced signal strength method, the location system uses information captured and transmitted by the locator. Some devices are equipped with an option to block such transmissions, preventing the system from locating the device. But in network-based locator systems that measure the locator's signal characteristics without requiring its cooperation, the only safe way for users to keep their locations secret is to turn off the device.

## MORE WORK TO BE DONE

Despite the strides made in recent years in personal locator technologies [Table 2], much work remains to be done on their accuracy, locator miniaturization, battery life, multipath effects, ability to penetrate buildings, and the economical use of RF bandwidth. In addition, hybrid systems may be required to provide improved coverage and open the door to new applications.

Reducing the cost of deploying location technology is essential in removing barriers to the use of location services. The concern over how to pay for E911 services demonstrates the need for cost reduction. However, if a rich set of location services could share the expense of the additional infrastructure needed to support these services, the cost per subscriber would be reduced. The new location technologies, as well as wireless data packet services, that are now emerging around the globe offer opportunities for entrepreneurs to expand personal locator services.

In June 1999, Loc8.net (www.loc8.net), based in Seattle, Wash., announced that in late 2000 it intends to provide location-based services employing the ReFLEX two-way paging wireless infrastructure. The services, which will use wireless assisted GPS, will include personal locator services for Alzheimer patients and children as well as commercial services such as fleet management. The two-way paging systems using ReFLEX, developed by Motorola Inc. of Schaumberg, Ill., cover 95 percent of the U.S. population. The Loc8.net system operates in emergency and paging modes.

Recent advances such as assisted GPS are likely to enhance GPS-based offender-monitoring systems, reducing device size and power consumption, adding to accuracy, and offering new capabilities like in-building tracking.

In the future, personal locators could bring many other blessings. Equipping young children with personal locators may offer parents greater peace of mind. Small enough locators could even track pets.

Personal locators could also be helpful to medical patients where the locator would be combined with a detector that monitors the patient's vital signs. If the detector picked up abnormalities in the signals, it would alert the nurse or physician with both medical and location information. Such a service could offer a patient greater freedom and a shorter stay in hospital or nursing home. Its greatest contribution, however, may be peace of mind for patients, their families, and doctors.

Obviously, technical and commercial considerations will determine the success of the technology. Issues of users' privacy and confidentiality will, however, have to be addressed first. ◇

## TO PROBE FURTHER

Information on an RF identification system for a local positioning system is available in "Designing a positioning system for finding things and people indoors," by Jay Werb and Colin Lanzl, *IEEE Spectrum*, September 1998, pp. 71–78.

A review of mobile wireless telephony past and future, including data services, appeared in *Spectrum* last year. See "The mobile telephone meets the Internet," by Malcolm W. Oliphant, August 1999, pp. 20–28.

Overviews of non-global positioning system (GPS) geolocation techniques and geolocation services are provided in an *IEEE Communication Magazine* issue dedicated to geolocation systems and services, April 1998, Vol. 36, pp. 28–76.

A discussion of the time difference of arrival (TDOA) and the GPS problem and their solutions, complete with historical perspective, is available in "The GPS Equations and the Problem of Apollonius," a paper by Joseph Hoshen that appeared in *IEEE Transactions on Aerospace and Electronic Systems*, July 1996, Vol. 32, no. 2, pp. 1116–24).

A comprehensive description of GPS and its application is available from *Understanding GPS Principles and Applications*, edited by Elliot D. Kaplan (Artech House, Norwood, Mass., 1996).

## ABOUT THE AUTHORS

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Joseph Hoshen (M) has been active in the area of offender monitoring. In 1998, he received a grant from the National Institute of Justice (NIJ) to study wide-area continuous offender-monitoring systems. He is also recognized for the development of the widely used Hoshen-Kopelman algorithm, which is currently used in processing very large images and lattices in science and engineering. He can be reached by e-mail at jhoshen@worldnet.att.net.

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# Standardization of mobile phone positioning for 3G systems

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**Abstract:**
Finding the location of the mobile phone is one of the important features of the 3G mobile communication system. Many valuable location-based services can be enabled by this new feature. Telecommunication managers and engineers are often puzzled by location terminologies and techniques as well as how to implement them, since location systems are not natural evolution from past generations of telecommunication systems. In this paper, we discuss briefly why locating mobile phone becomes a hot topic and what technologies are being studied. We then describe and clarify the latest standards issues surrounding the positioning methods specified for 3G systems. These include cell-ID-based, assisted GPS, and TDOA-based methods, such as OTDOA, E-OTD, and A-FLT

**Index Terms:**
Global Positioning System cellular radio standardisation telecommunication standards

**Documents that cite this document**
Select link to view other documents in the database that cite this one.

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# Standardization of Mobile Phone Positioning for 3G Systems

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## ABSTRACT

Finding the location of the mobile phone is one of the important features of the 3G mobile communication system. Many valuable location-based services can be enabled by this new feature. Telecommunication managers and engineers are often puzzled by location terminologies and techniques as well as how to implement them, since location systems are not natural evolution from past generations of telecommunication systems. In this paper, we discuss briefly why locating mobile phone becomes a hot topic and what technologies are being studied. We then describe and clarify the latest standards issues surrounding the positioning methods specified for 3G systems. These include cell-ID-based, assisted GPS, and TDOA-based methods, such as OTDOA, E-OTD, and A-FLT.


## INTRODUCTION

The U.S. Federal Communications Commission (FCC) has made Emergency 911 (E911) a mandatory requirement for wireless communications services such as cellular telephone, wideband (broadband) personal communications services (PCS), and geographic area specialized mobile radio (SMR). This ruling and upcoming service is called wireless E911. For Phase II implementation, the FCC required that public safety answering point (PSAP) attendants of wireless communications networks must be able to know a 911 caller's phone number for return calls and the location of the caller so that calls can be routed to an appropriate PSAP and related emergency assistance attendants. In 1999 the FCC decided to tighten the Phase II location accuracy requirement from 125 m in 67 percent of all cases to new numbers: for handset-based solutions, 50 m in 67 percent of calls and 150 m in 95 percent of calls; for network-based solutions, 100 m in 67 percent of calls and 300 m in 95 percent of calls. Handset-based solutions are for nonlegacy phones. Network-based solutions are for legacy phones. In 2000 the FCC required wireless communications operators to offer operational location-capable phones by October 1, 2001. On September 8, 2000, the FCC granted a limited waiver to VoiceStream with relaxed accuracy for an extended period. Right after the October deadline of 2001, waivers were granted to Alltel, AT&T Wireless, Cingular, NEXTEL, Sprint PCS, and Verizon, permitting them to postpone selling and activating location-capable phones that satisfy the new numbers until 2002 or later.

The executive body of the European Union (EU), the European Commission (EC), has similar initiatives for their wireless emergency calls, E112. Coordination groups within EC have been organizing meetings to specify similar requirements as their counterpart in the United States. On March 26, 2002, EU transport ministers approved $482.4 million in funding for the development of the European satellite system, called Galileo. This new system will rival the U.S.-developed global positioning system (GPS), which has already been adopted as one of the technologies for positioning, as discussed later.

In the United States, a recent survey by Harris Interactive indicated that consumers were more interested in E911 than other new mobile phone features. Out of 1006 adults, 59 percent selected E911 service. At a distant second, 7 percent selected e-mail service.

Besides emergency assistance, wireless E911 and its positioning capability will certainly trigger and enhance many location-based services. For instance, the telematics system [1] currently offered by automotive manufacturers, such as GM's OnStar and Mercedes-Benz's TeleAid, can be improved significantly. Future systems may no longer need to have separated location and communication devices attached permanently to the vehicle. Therefore, it is not difficult to understand why telecommunications manufacturers and operators have been actively pursuing the technologies to locate the mobile phone.

In this article we discuss location technologies specified by the 3rd Generation Partnership Project (3GPP) and 3GPP2, respectively. 3GPP has been concentrating on wideband code-division multiple access (W-CDMA) and Global System for Mobile Communications (GSM) systems while 3GPP2 has been focusing on cdma2000 and cdmaOne systems.


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## Basic Location Technologies

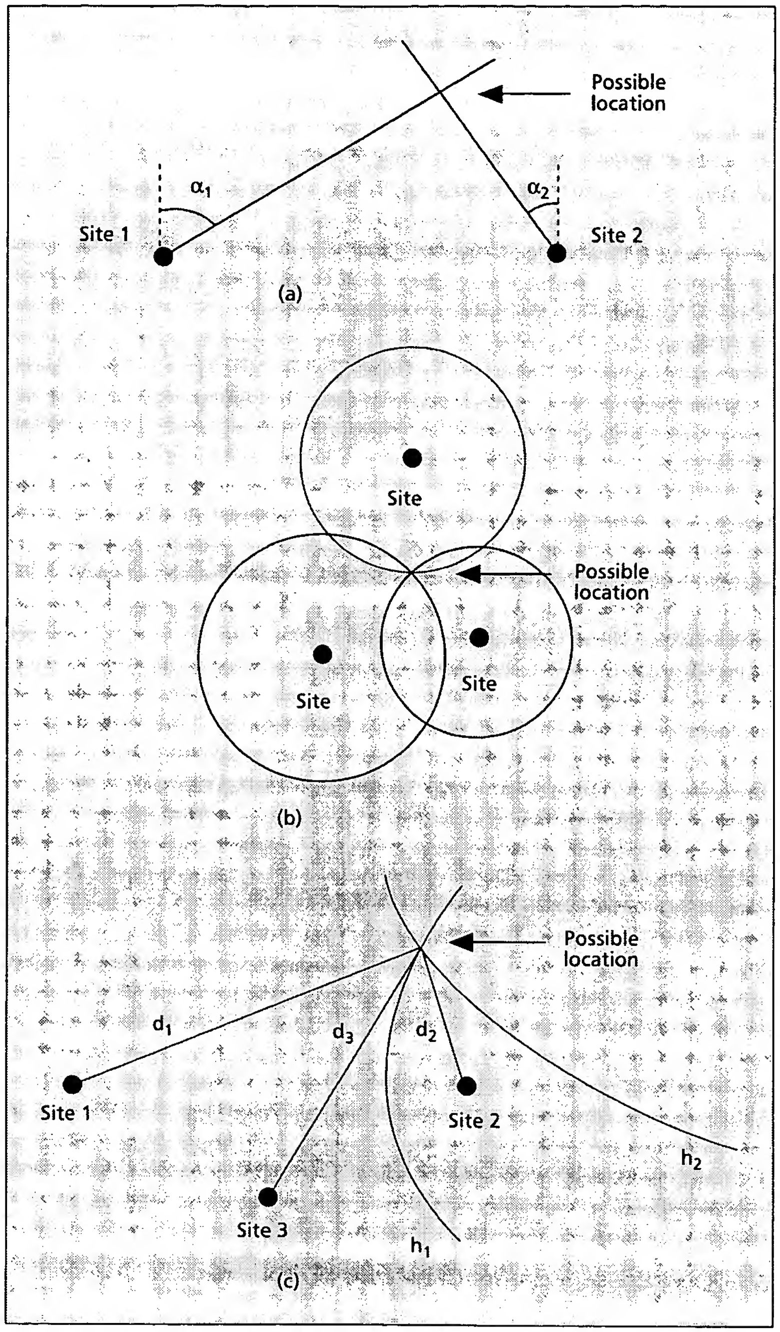
There are three most commonly used location technologies: standalone, satellite-based, and terrestrial-radio-based [2]. As examples, a typical standalone technology is dead reckoning; a typical satellite-based technology is GPS; and a typical terrestrial radio-based technology is the "C" configuration of the Long Range Navigation (LORAN-C) system. For wireless E911, E112, and many other applications, radio-based (satellite and terrestrial) technologies are most popular. Cellular networks are terrestrial-based communications systems. It is natural to utilize the signals of the network to determine the mobile phone location or assist in location determination. Research in this area has been very active recently as evidenced by the latest round of publications and conferences. The principles behind them are discussed below.

Radio-based technology typically uses base stations, satellites, or other devices emitting radio signals to the mobile receiver to determine the position of its user. Signals can also be emitted from the mobile device to the base. Commonly studied techniques are *angle of arrival* (AOA) positioning, *time of arrival* (TOA) positioning, and *time difference of arrival* (TDOA) positioning. All these methods require radio transmitters, receivers, or transceivers. In other words, they depend on emitting and receiving radio signals to determine the location of an object on which a radio receiver or transceiver is attached. To make the position determination, these methods generally work under the assumption that one end of the positioning system is fixed or known and the other movable (e.g., a mobile phone). However, the location determination capability can be at either the fixed or the mobile end. Generally, it is up to the system designer to decide where the final location determination capability should reside. For performance improvement, hybrid methods (various combinations of the techniques discussed or with additional techniques) are possible. To simplify our discussion, in the following we use two-dimensional (2D) cases as application examples. Readers should be able to expand the principles presented to 3D cases.

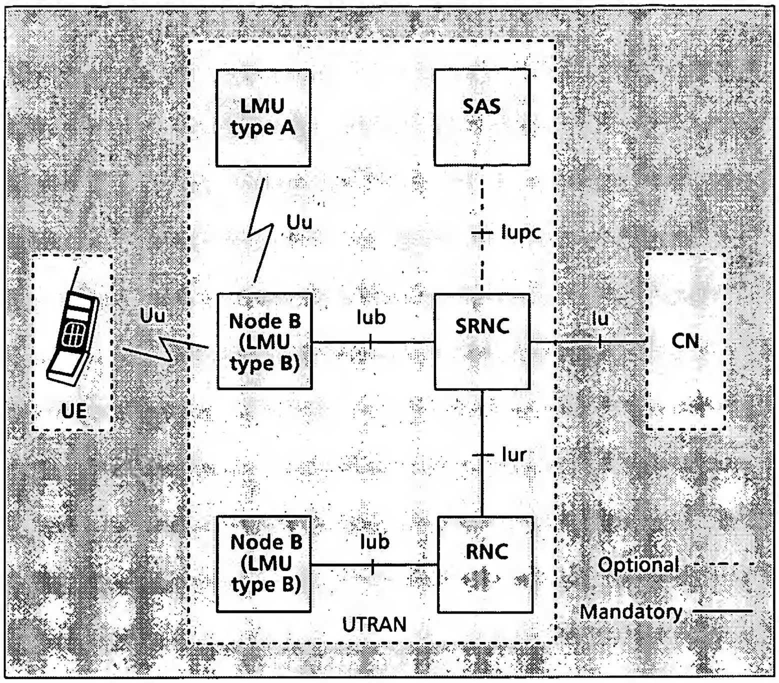
The AOA system determines the mobile phone position based on triangulation, as shown in Fig. 1a. It is also called direction of arrival in some literature. The intersection of two directional lines of bearing defines a unique position, each formed by a radial from a base station to the mobile phone in a 2D space. This technique requires a minimum of two stations (or one pair) to determine a position. If available, more than one pair can be used in practice. Because directional antennas or antenna arrays are required, it is difficult to realize AOA at the mobile phone.

The TOA system determines the mobile phone position based on the intersection of the distance (or range) circles (Fig. 1b shows a 2D example). Since the propagation time of the radio wave is directly proportional to its traversed range, multiplying the speed of light to the time obtains the range from the mobile phone to the communicating base station. Two range measurements provide an ambiguous fix, and three measurements determine a unique position. The same principle is used by GPS, where the circle becomes the sphere in space and the fourth measurement is required to solve the receiver-clock bias for a 3D solution. The bias is caused by the unsynchronized clocks between the receiver and the satellite.

The TDOA system determines the mobile phone position based on trilateration, as shown in Fig. 1c. This system uses time difference measurements rather than absolute time measurements as TOA does. It is often referred to as the *hyperbolic system* because the time difference is converted to a constant distance difference to two base stations (as foci) to define a hyperbolic




■ **Figure 1.** *Position determination methods: a) angle of arrival; b) time of arrival; c) time difference of arrival.*




■ **Figure 2.** *System architecture of UE positioning.*

curve. The intersection of two hyperbolas determines the position. Therefore, it utilizes two pairs of base stations (at least three for the 2D case shown in Fig. 1c) for positioning. The accuracy of the system is a function of the relative base station geometric locations. For terrestrial-based systems, it also requires either precisely synchronized clocks for all transmitters and receivers or a means to measure these time differences. Otherwise, a 1 μs timing error could lead to a 300 m position error.

Other location methods can also be used. One simple method for mobile phone positioning is to use the cell area (or *cell ID*) of the caller, assisted by other coarse estimates, as the approximate location of the mobile phone. We will discuss this method further in the next section. Another method is to use *short-range beacons* (or signposts in some literature) installed in the coverage area to provide location-specific information to the mobile receiver [2]. Due to its limited communication zones, discontinuous communication, and high system installation and maintenance costs, it has not been considered for mobile phone positioning. Another alternative is to use *other radio signals*, such as TV or AM/FM radio broadcast signals, in place of cellular or satellite signals. In most areas there are plenty of these radio signals. The coverage is generally better than that provided by cellular signals. Other methods are based on measuring the *signal strength* or *signal characteristic patterns* and multipath characteristics of radio signals arriving at a cell site from a caller. For measuring the signal strength, it employs multiple cell sites to find the location. For measuring the signal characteristic patterns, it identifies the unique radio frequency pattern or *signature* of the call and matches it to a similar pattern stored in its central database.

## Location Technologies Specified by 3GPP

### Location Technologies Specified for UTRAN

In the Universal Terrestrial Radio Access Network (UTRAN), a handset is called user equipment (UE) and a base station is called node B. There are two operational modes for UTRAN: frequency-division duplex (FDD) and time-division duplex (TDD). The original standards specifications were developed based on FDD mode.

Three location techniques have been specified for UTRAN [3–8]: the cell-ID-based, observed TDOA (OTDOA), and assisted GPS (A-GPS) methods. When the mobile phone position is calculated at the network, we call it a UE-assisted solution. When the position is calculated at the handset, we call it a UE-based solution. Note that except for the UE-assisted OTDOA method, the rest of the methods are optional in the UE.

Figure 2 illustrates the system architecture of UE positioning (UP). The UTRAN interfaces (Uu, Iub, Iur, and Iupc) are used to communicate among all relevant entities. In this figure SRNC stands for serving radio network controller, LMU for location measurement unit, SAS for standalone serving mobile location center (SMLC), and CN for core network. LMU type A is a standalone LMU; type B is integrated with a base station.

For Release 99 (standards release frozen in December 1999) and Release 4 (frozen in March 2001), the SAS supports A-GPS only. In Release 5 (frozen in March 2002), the SAS will support two other location methods as well (Cell ID and OTDOA). Deployment of the SAS is optional. If an SAS is not included in the system, the SMLC (location server) will be an integral part of the RNC or SRNC. Note that later releases have more features (functionalities) than early ones. "Frozen" means that the contents (or features) of a specific release have been decided, but the detailed protocols and functionalities may not be stable or finalized. These releases are updated quarterly.

***The Cell-ID-Based Positioning Method —*** The cell-ID-based method determines the UE position at the network. In other words, the position of a UE is estimated based on the coverage information of its serving node B. This knowledge can be obtained by paging, locating area update, cell update, UTRAN registration area (URA) update, or routing area update. This method is optional for the network. Despite not being mandatory, it is the author's suggestion that we should implement it as a default location method. Whenever OTDOA or A-GPS fails to locate the UE, we can always use this method to provide approximate information on mobile phone position to the network.

Depending on the operational status of the UE, additional operations may be needed in order for the SRNC to determine the cell ID. When the location service (LCS) request is received from the CN, the SRNC checks the state of the target UE. If the UE is in a state where the cell ID is not available, the UE is

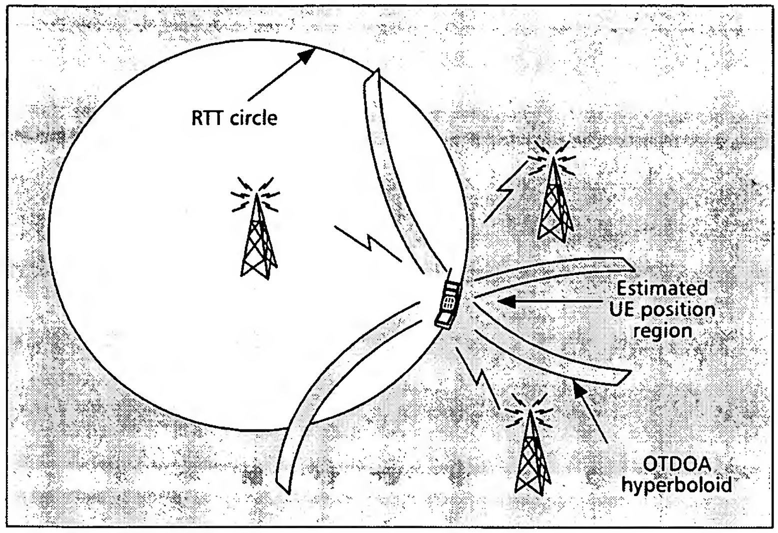
paged so that the SRNC can establish the cell with which the target UE is associated. In states where the cell ID is available, the target cell ID is chosen as the basis for the UE positioning. In soft handover, the UE may have several signal branches connected to different cells while reporting different cell IDs. The SRNC needs to combine the information about all cells associated with the UE to determine a proper cell ID. The SRNC should also map the cell ID to geographical coordinates or a corresponding service area identity (SAI) before sending it from the UTRAN to the CN. This can easily match the service coverage information available in the CN.

In order to improve the accuracy of the LCS response, the SRNC may also request additional measurements from node B or the LMU. These measurements are originally specified for soft handover. For FDD mode, round-trip time (RTT) can be used as a radius of a cell to further confine the cell coverage. RTT is the time difference between the transmission of the beginning of a downlink dedicated physical channel (DPCH) frame to a UE and the reception of the beginning of the corresponding uplink from the UE. For TDD mode, received (RX) timing deviation can be used. RX timing deviation is the time difference between the reception in node B of the first detected uplink path and the beginning of the respective slot according to the internal timing of node B. The measurements are reported to higher layers, where timing advance values are calculated and signaled to the UE. For better accuracy, for instance in FDD mode, a mandatory UE Rx-Tx time difference type 1 or an optional type 2, if available, can be combined with RTT to determine the distance from a node B to a UE. UE Rx-Tx time difference is the difference between the UE uplink DPCCH/ DPDCH frame transmission and the first detected path (in time) of the downlink DPCH frame from the measured radio link, where DPCCH stands for dedicated physical control channel and DPDCH stands for dedicated physical data channel. The main differences in type 1 and type 2 are the measurement resolution and reference Rx path (or first detected path). For type 2, the resolution is better and the reference path must be the path among all paths detected by the UE. In contrast, for type 1, the reference path is the one used in the demodulation process.

The cell-ID-based method should determine the position of the UE regardless of the UE operational mode (i.e., connected or idle). This method results in a position error as large as the cell area if no additional measurements are used. For instance, a picocell could be 150 m in radius, while a large cell could be more than 30,000 m in radius. Therefore, this method has not demonstrated that it can achieve 100 m accuracy reliably even under the best of conditions.

***The OTDOA Positioning Method*** — OTDOA is a TDOA-based positioning method. It determines the position of the mobile phone based on trilateration as shown in Fig. 3. Two methods are specified for OTDOA: UE-assisted OTDOA and UE-based OTDOA.

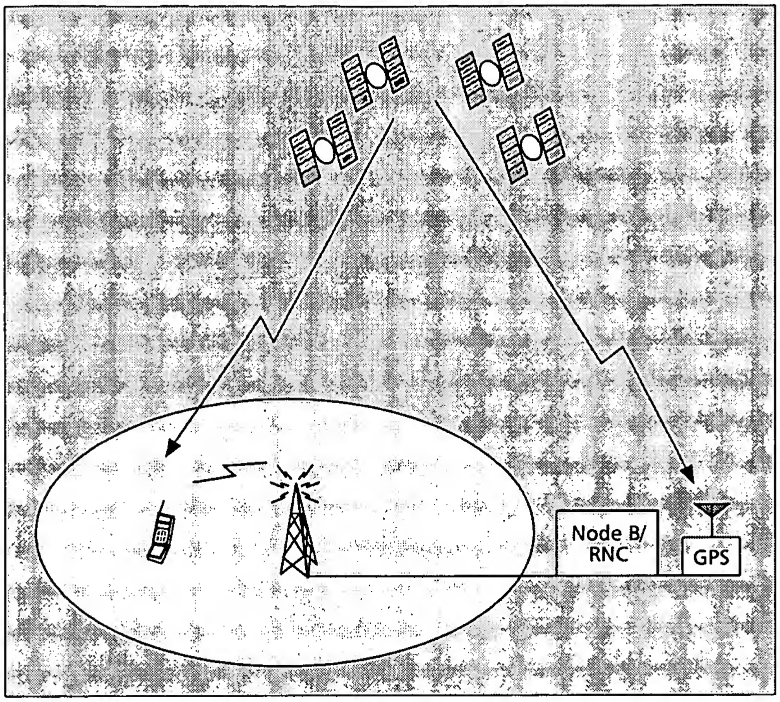
As discussed above for a TDOA-based




■ **Figure 3.** *OTDOA positioning method.*

method, the accuracy of the system is a function of the relative node B geometric locations. Additional environmental constraints dictate that the more measurements we can obtain, the better position fixes we will receive. Since these measurements are based on the signals from node Bs, the locations of these base stations are necessary for the network or UE to calculate the handset positions. If the transmitters of node B in UTRAN are unsynchronized, the relative time difference (RTD) must be provided for system frame numbers (SFN). It is named SFN-SFN observed time difference. One way to obtain these measurements is to deploy LMUs, which perform timing measurements of all the local transmitters in fixed locations of the network. These measurements can be converted to RTDs and transmitted to the UE or RNC for positional calculations. In addition, the UE also measures the SFN-SFN observed time difference, which identifies the time difference between two cells as TDOA. Two types are defined. As explained later, type 1 is used for soft handover and type 2 is used for positioning. The main difference of these two types is that type 2 is applicable for both idle and connected modes, while type 1 supports intrafrequency measurements and cannot do interfrequency measurements for the connected mode. Since node Bs in TDD mode are generally synchronized, the RTDs are typically constant. Similarly, in FDD if the relevant cells are synchronized, measurements of RTDs would not be necessary. For FDD mode, RTT and Rx-Tx time difference can be obtained to improve the performance of the OTDOA. For TDD mode, RX timing deviation can be obtained to improve performance. Since adaptive or smart antennas have been specified as a feature for 1.28 Mchips/s TDD networks, AOA can be used to further improve the OTDOA and cell ID performances.

The OTDOA location method in UTRAN has its problems, such as hearability, unsynchronized base stations for FDD mode, geometric location of the base stations, and capacity loss. For the hearability problem, this can occur when the UE is very close to its serving node B, which




■ **Figure 4.** *Assisted GPS positioning method.*

could block the reception of other base station signals in the same frequency. From Fig. 3 we know the UE must be able to hear at least three base stations in order to perform its location duty. For the unsynchronized base station problem, it causes significant uncertainty to the TDOA measurements. For the geometric location of the base station problem, the locations of the contributing base stations could affect the availability and quality of the position fixes. For instance, on a long straight highway in a rural area, OTDOA may fail to produce required solutions because node Bs may simply lie along the same highway. For the capacity loss problem, the system could provide less capacity to customers since the signal and traffic channels as well as some of the computing power of the UE or network entity could be occupied by the location services.

In order to improve the hearability of neighboring node Bs, one option specified is the idle period downlink (IPDL). In this method, each node B ceases its transmission for short periods of time (idle periods). During an idle period of a node B, UEs within the cell can measure other node Bs, so the hearability problem is reduced. By using signaling over the Uu interface, UEs are made aware of the occurrences of IPDLs, so they can arrange the time difference measurements accordingly. Since the IPDL method is based on downlink, the location service can be provided efficiently to a large number of UEs simultaneously.

For UE-assisted OTDOA, essential information elements (IEs) or assistance data from UTRAN to UE are reference and neighbor cell information. For UE-based OTDOA, they are reference and neighbor cell information as well as node B positions of these cells. UE-assisted OTDOA is mandatory for the UE and optional for the UTRAN. The UE-based OTDOA is optional for both the UE and UTRAN. Notice that for UE-based OTDOA, the length of the downlink IE is longer than the UE-assisted OTDOA. In contrast, the length of the uplink IE is shorter since one reports 2D/3D UE position and another reports measured TDOA results. In addition, UTRAN-to-UE information transfer is specified for both point-to-point and broadcast transmissions. For broadcast, UE-assisted OTDOA IEs are defined as system information block type 15.4 and UE-based OTDOA IEs are defined in as system information block type 15.5 [8].

***The Assisted GPS Positioning Method*** — GPS provides an affordable means to determine position, velocity, and time around the globe. The satellite constellation is developed and maintained by the U.S. Department of Defense. Civilian access is guaranteed through an agreement with the Department of Transportation. GPS satellites transmit two carrier frequencies. Typically, only one is used by civilian receivers. From the perspective of these civilian receivers, GPS satellites transmit at 1575.42 MHz using CDMA, which uses a direct-sequence spread-spectrum (DS-SS) signal at 1.023 MHz (Mchips/s) with a code period of 1 ms. Each satellite's DS-SS signal is modulated by a 50 b/s navigation message that includes accurate time and coefficients (ephemeris) to an equation that describes the satellite's position as a function of time. The receiver (more precisely, its antenna) position determination is based on TOA.

The four main conventional GPS receiver functions are:

- Measuring distance from the satellites to the receiver by determining the pseudo-ranges (code phases)
- Extracting the TOA of the signal from the contents of the satellite transmitted message
- Computing the position of the satellites by evaluating the ephemeris data at the indicated TOA
- Calculating the position of the receiving antenna and the clock bias of the receiver by using the above data items

Position errors at the receiver are contributed by the satellite clock, satellite orbit, ephemeris prediction, ionospheric delay, tropospheric delay, and selective availability (SA). SA is an accuracy degradation scheme to reduce the accuracy available to civilian users to a level within the national security requirements of the United States. It decreases the accuracy capability of autonomous GPS to the 100 m (2D-RMS) level, where RMS stands for root mean square. To reduce these errors, range and range-rate corrections can be applied to the raw pseudo-range measurements in order to create a position solution that is accurate to a few meters in open environments. The most important correction technique is differential GPS (DGPS). It uses a reference receiver at a surveyed position to send correcting information to a mobile receiver over a communications link. Note that since May 2000 SA has been turned off, which often results in an accuracy of under 20 m in unobstructed environments.

To deal with the following problems facing the standalone conventional GPS receiver, the A-GPS method was specified to improve the performance of GPS (Fig. 4):

- Its startup time (from turning on to the initial position fix) is relatively long due to the long acquisition time of the navigation message (at least 30 s to a few minutes).
- It is unable to detect weak signals that result from indoor and urban canyon operations as well as small cellular-sized antennas.
- Its power dissipation is relatively high per fix, primarily due to the long signal acquisition time in an unaided application.

The basic idea of assisted GPS is to establish a GPS reference network (or a wide-area DGPS network) whose receivers have clear views of the sky and that can operate continuously. This reference network is also connected with the cellular infrastructure, continuously monitors the real-time constellation status, and provides data such as approximate handset position (or base station location), satellite visibility, ephemeris and clock correction, Doppler, and even the pseudorandom noise code phase for each satellite at a particular epoch time. At the request of the mobile phone or location-based application, the assist data derived from the GPS reference network are transmitted to the mobile phone GPS receiver (or sensor) to aid fast startup and increase sensor sensitivity. Acquisition time is reduced because the Doppler vs. code phase uncertainty space is much smaller than in conventional GPS due to the fact that the search space has been predicted by the reference receiver and network. This allows for rapid search speed and a much narrower signal search bandwidth, which enhances sensitivity and reduces mobile receiver power consumption. Once the embedded GPS receiver acquires the available satellite signals, the pseudo-range measurements can be delivered to RNC or SAS in UTRAN for position calculation or used internally in the UE to compute position.

Additional assisted data, such as real-time integrity, DGPS corrections, satellite almanac, ionospheric delay, and universal time coordinated (UTC) offset can be transmitted to improve the location accuracy, decrease acquisition time, and allow for different position computation solutions. Besides adding a GPS reference network and additional location determination units in the network, the mobile phone must embed, at a minimum, a GPS antenna and RF downconverter circuits, as well as make provision for some form of digital signal processing software or dedicated hardware. Despite the fact that A-GPS can improve the performance of a conventional GPS receiver, it cannot be used for legacy phones already on the market. As in the case of OTDOA, there are two solutions for A-GPS. A UE can support either one or both of them.

The UE-assisted solution shifts the majority of the traditional GPS receiver functions to the network processor. This method requires an antenna, RF section, and digital processor in the UE for making measurements by generating replica codes and correlating them with the received GPS signals. The network transmits an assistance message to the mobile station, consisting of time, visible satellite list, satellite signal Doppler and code phase, as well as their search windows or, alternatively, approximate handset position and ephemeris. These IEs help the embedded GPS sensor reduce the GPS acquisition time. The assistance data of Doppler and code phase are valid for a few minutes, while ephemeris data last two to four hours. It returns from the UE the pseudo-range data processed by the GPS sensor. After receiving the pseudo-range data, the location server in the SRNC or SAS estimates the position of the UE. The differential correction (DGPS) can be applied to the pseudo-range data or final result at the network side to improve the position accuracy.

The UE-based solution maintains a fully functional GPS receiver in the handset. This requires the same functionality described for UE-assisted GPS, plus additional means for computing the positions of the satellites and ultimately the UE's position. This additional handset function generally adds to the handset's total memory (RAM, ROM) requirements in addition to extra computing capability such as million instructions per second (MIPS). In the initial startup scenario, data in the form of the precise satellite orbital elements (ephemeris) must be provided to the UE. This data is valid for two to four hours and can be extended to cover the entire visible period of the GPS satellite (i.e., up to 12 hours), as discussed later. Thus, once the handset has the data, subsequent updates are rare. For better positional accuracy or longer ephemeris life, differential correction (DGPS) data should be transmitted to the UE. The final position of the UE is generated at the UE itself. The calculated UE position can then be sent to an application outside of the UE if required.

For UE-assisted GPS, the essential IEs from UTRAN to UE are reference UE position, GPS reference time, plus either code phase and Doppler (acquisition assistance) or satellite positions (ephemeris and clock correction). For UE-based GPS, they are reference UE position, GPS reference time, plus satellite positions and failed/failing satellites information (real-time integrity). The UE can also request additional GPS IEs. From UE to UTRAN, UE-assisted GPS reports measured pseudo-range results, while UE-based GPS reports 2D/3G UE position. For UE-based GPS, UTRAN-to-UE information transfer is specified for both point-to-point and broadcast transmission. For broadcast, the essential IEs are defined as system information block types 15 and 15.2 [8].

There are some interesting features defined in the specifications to improve the performance of the A-GPS. In the DGPS corrections IE [8], three pairs of pseudo-range correction (PRC) and range-rate correction (RRC) related fields are specified. Proper usage of these pairs will extend the life of the ephemeris and clock correction IE [8], which in turn will reduce transmission bandwidth, handset power consumption, memory, and CPU load. Typically, the ephemeris IE is valid at the UE for 2–4 h. The PRC2/RRC2 pair is used to extend the life for 6 h and the

*The basic idea of assisted GPS is to establish a GPS reference network (or a wide-area DGPS network) whose receivers have clear views of the sky and which can operate continuously. This reference network is also connected with the cellular infrastructure.*

*The basic idea is to remove the errors contained in the ephemeris IE when needed. Since the maximum visible period of GPS satellites for one path is 12 hours, this feature avoids transmitting the long ephemeris IE more than once during the period.*

| Pros/Cons | UE-Based GPS | UE-Assisted GPS |
|---|---|---|
| Advantage | Relatively short uplink IE | Relatively short downlink assistance IE if code phase and Doppler are used |
| | Assistance IE valid for 2–4 hours or up to 12 hours at the UE if ephemeris life extension feature is used (less signaling) | Network in control of position determination |
| | Good for tracking/navigation applications | Need less computing power and memory at the UE |
| | Can be used as a standalone GPS receiver | |
| | Do not need LMU | |
| Disadvantage | Relatively long downlink assistance IE | Relatively long uplink IE |
| | Need more computing power and memory at the UE | Assistance IE valid for a few minutes at the UE if code phase and Doppler are used (more signaling for tracking/navigation applications) |
| | | Need accurate timestamps at the UE |
| | | Certain event trigger mechanisms will not work |
| | | Need LMU for certain assistance data |

■ **Table 1.** *Comparison of UE-assisted and UE-based GPS.*

PRC3/RRC3 pair is used for 8 h. To extend the life of the ephemeris IE beyond 8 h in broadcast or beyond 2–4 h in point-to-point operations, tailored DGPS can be used: a UE informs the RNC or SAS of its issue of data ephemeris (IODEs) and expected use time of its stored ephemeris [8]; then the RNC provides a PRC/RRC pair specific to that UE. The basic idea is to remove the errors contained in the ephemeris IE when needed. Since the maximum visible period of GPS satellites for one path is 12 h, this feature avoids transmitting the long ephemeris IE more than once during the period. By using this method, a UE wakes up for a particular correction pair only when a location fix is required.

The real-time integrity IE [8] is essential for proper operation of A-GPS. What this message covers is abnormal situations out of the control of the GPS control segment (master stations on the ground). For example, the atomic clock of a GPS satellite can fail suddenly, which in turn produces wrong satellite signals. In other words, the location accuracy can degrade substantially when undetected GPS satellite failures are present. Such failures can render the positioning information derived by a UE completely unusable. Although the control segment monitors the health of the GPS satellites, this activity is not performed continuously. It may require more than 30 min for the control segment to communicate this to GPS users. To provide the real-time integrity IE, one has to deploy an integrity monitor (IM) in the RNC or SAS. Besides informing of failed/failing satellites, it also tells the UE of measurement quality when satellites are healthy. This is done through the supplied user differential range error (UDRE), which is one field in the DGPS correction IE. The UE uses the UDRE as a factor in weighing data obtained from associated satellites in its position calculation.

The above features are also specified in GSM standards. To reduce infrastructure investment, a shared location server can be implemented to support dual-mode phones operating in both GSM and UMTS/W-CDMA networks. An additional benefit of implementing these features is that the RNC or SAS has to provide differential capability to the system. This capability can greatly improve positioning performance, such as with unexpected multipath in the server and poor geometry of visible satellites for the UE.

Finally, in order to better understand the A-GPS method, we list the pros and cons of UE-based and UE-assisted GPS in Table 1. Readers can compare them to decide which is suitable for their specific application.

To clarify positioning measurements, Table 2 lists all UE and UTRAN related measurement elements. For UE, three elements are specified for other purposes. SFN-SFN observed time difference type 1 is used to identify the time difference between two cells. SFN-CFN observed time difference is used for handover timing purpose to identify active cell and neighbor cell time difference, where CFN stands for connection frame number. Note that SFN-CFN observed time difference is defined as cell synchronization information in radio resource control protocol [8]. Both are used for soft handover. The difference is that SFN-SFN is for establishment of a call directly into soft handover, and SFN-CFN is for addition of new radio links into the soft handover for an already existing call. Rx-Tx timing difference type 1 is used for call setup purposes to compensate for the propagation delay between uplink and downlink transmissions, and to tell the network that the received timing of a cell is moving out of the UE's soft combining window. In addition to soft handover, it can also be used to improve position determination performance. For UTRAN, all the elements listed are optional

| | Element | Accuracy (chips) | Choice | Comment |
|---|---|---|---|---|
| UE | Rx-Tx time difference type 1 | 1.5 for FDD | Mandatory | For soft handover |
| | Rx-Tx time difference type 2 | TBD for FDD | Optional | For position determination |
| | SFN-SFN observed time difference type 1 | 1 for FDD, 0.5 for TDD | Mandatory | For soft handover of establishing a call |
| | SFN-SFN observed time difference type 2 | 0.5 for FDD intra-frequency, 1 for FDD inter-frequency, 0.5 for TDD | Mandatory | For position determination |
| | Cell synchronization information | 1 for FDD, 0.5 for TDD | Optional | For soft handover on an existing call |
| | GPS timing of cell frames | TBD (to be determined) | Optional | For UE-assisted GPS position determination |
| UTRAN | SFN-SFN observed time difference | 0.5 | Optional | For position determination |
| | RTT | 0.5 for FDD | Optional | Can also been used for position determination |
| | RX Timing Deviation | 0.5 for TDD | Optional | Can also been used for position determination |
| | GPS timing of cell frames | TBD | Optional | For position determination |

■ **Table 2.** *Measurement elements.*

and can be used for position determination. They are also been used for Uu, Iub, Iur, and Iupc interfaces, as shown in Fig. 2.

For 3.84 Mchips/s systems, 1 chip is about 0.26 μs. This translates to 78.125 m in range uncertainty. For 1.28 Mchip/s systems, 1 chip is about 0.78 μs. This translates to 234.375 m in range uncertainty.

### LOCATION TECHNOLOGIES SPECIFIED FOR GERAN

In the GSM EDGE Radio Access Network (GERAN), where EDGE stands for enhanced data rates for GSM evolution, three location methods are specified: cell ID, enhanced observed time difference (E-OTD), and A-GPS. They are all inherited and evolved from the methods specified for GSM. E-OTD is a TDOA positioning method based on the OTD feature already existing in GSM. In principle, it is similar to OTDOA but operates in TDMA-based networks. A-GPS method is similar to that specified for UTRAN, but with different IE lengths and formats. Note that GERAN has not adopted an uplink TOA method specified for GSM. Readers can refer to [9] for more information regarding these methods.

## LOCATION TECHNOLOGIES SPECIFIED BY 3GPP2

Advanced forward link trilateration (A-FLT) and A-GPS have been standardized by Telecommunications Industry Association's TR-45.5 as IS-801 (IS-801-1 is its addendum) [10]. The next release, IS-801-A, is being handled by 3GPP2. Unlike GSM and W-CDMA, cdmaOne and cdma2000 are time-synchronized systems. Therefore, time difference measurement from them is easier than for GSM and W-CDMA.

The basic idea of the A-FLT method is to measure the time difference (phase delay) between CDMA pilot signal pairs. Each pair consists of the serving cell pilot and a neighboring pilot. The time difference is converted to range information. Finally, the range data is used to form certain hyperbolic curves at which an intersection is defined for handset location. Since the principle of this method is not much different than TDOA, we will not discuss it in detail.

Although the essential A-GPS IEs specified in IS-801 are very similar to those defined in 3GPP for UE-assisted and UE-based A-GPS, IS-801 offers more options. In other words, it provides more than one way to accomplish the same task. For instance, two IEs are defined to provide the reference UE position, one based on spherical coordinates and one on Cartesian coordinates. Despite these additional options, it does not support DGPS and broadcast specified by 3GPP. The new release, IS-801-A, is likely to address these issues in addition to adding other features and utilizing new channels defined for cdma2000.

## CONCLUSIONS

In general, among the three methods specified, the cell-ID-based method has the worst positional accuracy, while A-GPS has the best positional accuracy. For cell-ID-based methods, the accuracy should be very close to the radius of the cell. For TDOA-based methods, it may achieve an accuracy of under 100 m in 67 percent of calls. For A-GPS methods, an accuracy of under 20 m is a very reasonable expectation in 67 percent of calls when SA is off. Many factors affect the performance of these methods, as discussed in the previous sections, such as cell sizes, hearability of other base stations, visibility of GPS satellites, and multipath. An experienced GPS user may notice that the accuracy of A-GPS in open sky environments is similar to an ordinary GPS receiver in the market. Meanwhile, an A-GPS receiver may have better coverage in obstructed

*It would be beneficial if 3GPP and 3GPP2, as well as 3GPP GERAN and 3GPP RAN, can study how to harmonize their respective application interfaces and positioning protocols in future releases.*

environments. Compared with other radio-based technologies, A-GPS typically has better accuracy, but worse coverage than TDOA/TOA/AOA in buildings and urban canyon areas. On the other hand, the solution quality of TDOA/TOA/AOA depends heavily on the geometric location of the contributing base stations. To further improve these methods, hybrid approaches can be used [9]. One example is to combine OTDOA and A-GPS. Another is to combine OTDOA and AOA. Current specifications have left the door open for such fusions.

In 3GPP, new UE positioning enhancement solutions have been postponed until existing methods have been finished and stable. These new solutions include a thin UE GPS method, an uplink TDOA method, and a cumulative virtual blanking method to replace IPDL. 3GPP RAN is still working on the impact study of IPDL on the quality of service and measurement performance of the UE, and the open interface to support all three positioning methods discussed. GERAN continues working on location service in Iu mode. The proposed new methods have to wait until Release 6 (standards release expected to be frozen in June 2003) to be considered.

In 3GPP2, work for the next standards release has already begun. It is very likely they will address the issues of supporting broadcast, DGPS, and other new features, as well as how to utilize new channels specified for cdma2000. It would be beneficial if 3GPP and 3GPP2, as well as 3GPP GERAN and 3GPP RAN, can study how to harmonize their respective application interfaces and positioning protocols in future releases, particularly those independent of multiple access techniques.

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